The Cenomanian/Turonian boundary in Sakhalin, Far East Russia: ammonites, inoceramids, foraminifera, and radiolarians

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Abstract   The Cenomanian–Turonian succession of faunal assemblages identified in Sakhalin has enabled the establishment of 10 ammonite, 7 inoceramid, 4 radiolarian, and 2 foraminiferal zones, which correlate relatively well with those recorded for the northeastern region of Russia (Kamchatka and Koryakia) and for Japan. The problems surrounding placement of the Cenomanian/Turonian boundary in Sakhalin and in adjacent areas are reviewed. Significant macrofaunal turnover and radiation have been identified across the (locally defined) Cenomanian/Turonian boundary, as well as in the middle Turonian for ammonites and in the upper Turonian for inoceramids. The first occurrences of the widely distributed Pacific ammonite *Jimboiceras planulatiforme* (Jimbo), the cosmopolitan ammonite *Fagesia*, and the inoceramid *Mytiloides* aff. *labiatus* (Schlötheim), define the base of the Turonian Stage. The succession of foraminiferal assemblages does not exhibit any major extinction at the Cenomanian/Turonian boundary; however, a temporary faunal restructuring occurred at that time. The radiolarian fauna appears to have survived this interval without marked taxonomic change; a diversity decrease took place later, near the middle/late Turonian boundary.

Keywords   Cenomanian; Turonian; biostratigraphy; bioevents; diversity; correlation; ammonites; inoceramids; foraminifera; radiolarians; Naiba Formation; Bykov Formation; Sakhalin; Russia

INTRODUCTION

Within the Upper Cretaceous Pacific paleobiogeographic realm, the placement of stage boundaries is problematic. As a consequence, there are uncertainties regarding inter-regional and global correlation. Cretaceous stage stratotypes were first established in European sections, but the Pacific is well known for the high degree of faunal endemism and provinciality (see, amongst others, Pokhialajnen 1988; Noda & Matsumoto 1998; Zonova & Yazykova 1998; Zakharov et al. 2002). These features hamper stratigraphic interpretation and paleogeographic reconstructions. However, stage boundaries are usually marked either by major faunal turnovers within certain fossil groups or by globally significant bioevents in the evolution of different faunal groups (Kauffman & Hart 1995). Such boundaries may be indicative of major eustatic, climatic, or other paleoenvironmental changes and so are likely to coincide, or nearly coincide, with regional zonal boundaries for different fossil groups. In the present paper, we continue our work (Yazykova 1996, 2002; Zonova & Yazykova 1998; Yazykova et al. 2002) on Upper Cretaceous stage boundaries in the northern Pacific province, with the emphasis on documentation of the Cenomanian/Turonian (C/T) boundary, the placement of which has been a matter of debate for some time. Unfortunately, the main criterion recommended at the Second International Symposium on Cretaceous Stage Boundaries (Brussels, 1995), namely, the first appearance of the ammonite *Watinoceras devonense* (see Bengtson 1996), can not be applied in north Pacific regions of Russia, due to the absence of this key species.

The C/T boundary bioevent is a relatively minor Phanerozoic mass extinction (Raup & Sepkoski 1984; Kauffman & Hart 1995) and is related to a 2nd-order sequence boundary (Kauffman 1985). Seven percent of marine animal families and 26% of genera became extinct (Harries 1993). Generally, the C/T boundary interval is widely recognised as one of the all-time sea-level highstands (see, e.g., Hancock & Kauffman 1979, Haq et al. 1987; Hallam 1992). The C/T extinction is closely associated in time with Oceanic Anoxic Event (OAE) 2 that was probably triggered by areal expansion of oxygen-poor waters (see, e.g., Elder 1989; Hirano & Takagi 1995; Vejmarn et al. 1998; Leckie et al. 2002). In the northwest Pacific province, OAE2
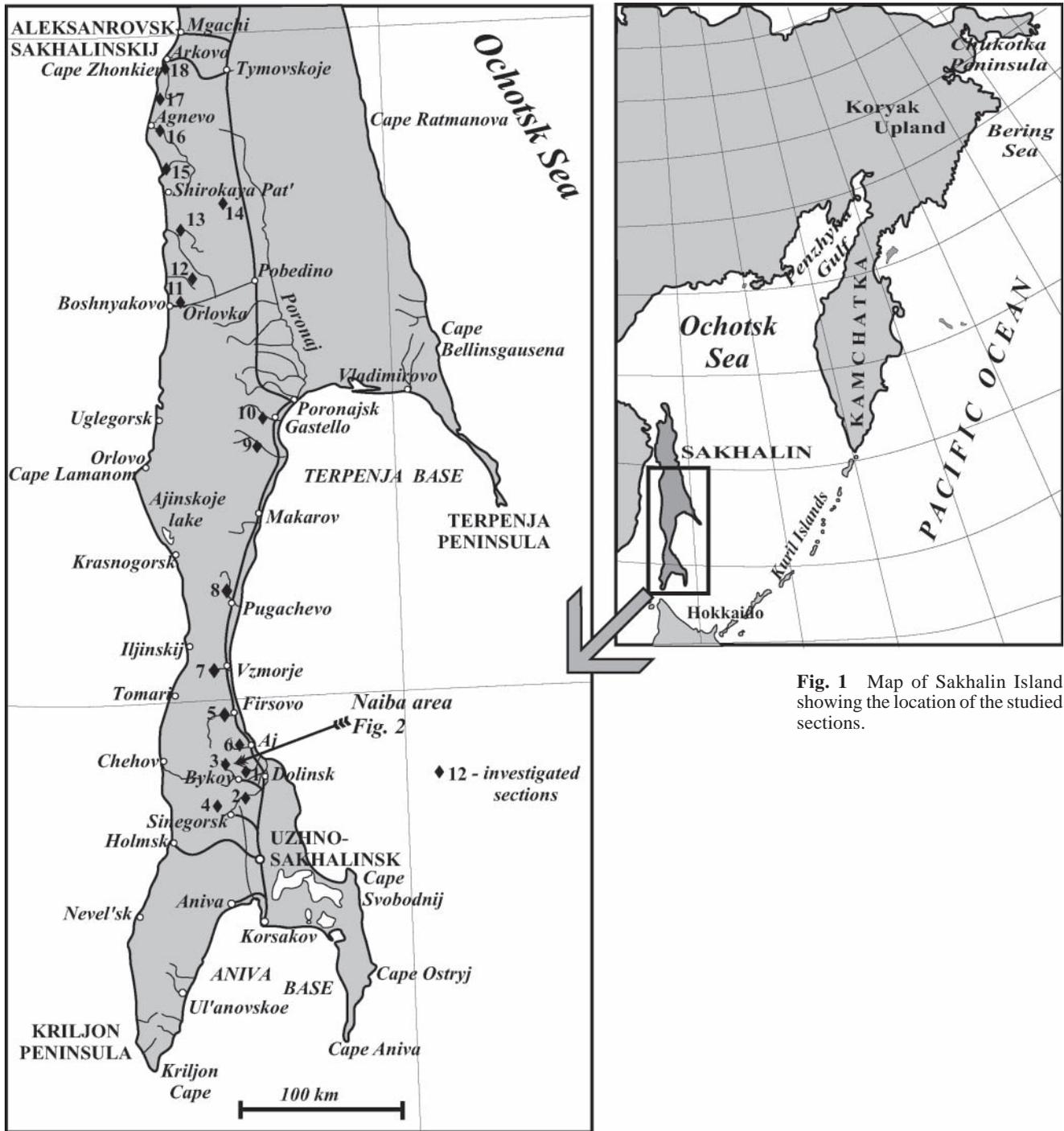
Fig. 1 Map of Sakhalin Island showing the location of the studied sections.

has been recorded from the top of the upper Cenomanian sequence in Hokkaido Island, Japan (Kaiho et al. 1993; Hirano & Takagi 1995; Toshimitsu & Hirano 2000). Generally, the carbon isotopic fluctuations recorded in terrestrial organic matter from the Hokkaido Cenomanian–Turonian (C–T) succession show a pattern that is remarkably similar to isotopic fluctuations in carbon reported from southern England, the Italian Appennines, and the Pueblo section (Hasegawa 1997). Unfortunately, isotopes and anoxic events have not been studied well in Far East Russia; however, Cenomanian anoxic events have been recorded by Japanese scientists in mudstone beds of the Middle Yezo Group, which are correlative with Sakhalin (Toshimitsu et al. 1995; see also Poyarkova 1987). It is possible that the Cenomanian OAE2 occurred in Sakhalin because, for example, the late Albian anoxic event (OAE1) recorded from the Lower Yezo Group has been documented in Japan as well as in Sakhalin (Hirano & Fukuju 1997). Moreover, Hasegawa et al. (2003) have recently recorded several carbon isotopic events, including a positive "spike" across the C/T boundary, in terrestrial organic matter from successions in the River Naiba valley, suggesting these could be correlated with those of carbonate carbon recorded from sections in other parts of the world.

The present paper discusses the recognition of the C/T boundary and coeval events in Sakhalin Island (Fig. 1), details

faunal characteristics of the C–T interval in the reference section of Cretaceous deposits (River Naiba valley) for four main groups, viz, ammonites, inoceramids, foraminifera and radiolarians, as well as addresses some possibilities for correlation between C–T sequences in Sakhalin and elsewhere.

MATERIAL AND METHODS

The present study is based on macrofauna collected from the River Naiba valley (Fig. 1, 2); in addition, one of us (EAY) collected almost 60 samples for microfaunal analyses during a field trip in 1999. Moreover, the authors have studied all specimens collected previously from the C–T sections N2–19 (Fig. 1) in Sakhalin; in fact, all conclusions are based on the entire material from the island. Prior to photography, macrofossils were coated with magnesium oxide. Photographs of microfossils are all SEM images. Inoceramids, ammonites, foraminifera, and radiolarians were identified by Zonova, Yazykova, Peryt, and Kazintsova, respectively.

For high-resolution faunal analyses and paleoecological reconstructions, data on non-inoceramid bivalves are mostly from Poyarkova (1987). Recent data on paleotemperatures (Zakharov et al. 1996, 1999; Kodama et al. 2000), based on $\delta^{18}O$ in sections in the southern part of Sakhalin Island, have also been incorporated, and all existing reference data on the C–T of Sakhalin Island have been assessed.

Specimens studied are housed in the VSEGEI (Vserosyjskij Nauchno-Issledovatelskij Geologicheskij Institut – All Russian Science Research Geological Institute) Museum (Saint Petersburg, Russia), at the University of Silesia, Faculty of Earth Sciences (Sosnowiec, Poland), and at the Institute of Paleobiology, Polish Academy of Sciences (Warsaw).

LITHOLOGY AND STRATIGRAPHY

In numerous sections around the world, sediments of the C–T interval are represented by specific marker lithofacies (e.g., black shales, black marl, black sand, red limestone, greenish clay or greenish sandstone), or geochemical evidence (Hallam & Wignall 1997; Vejmarn et al. 1998).

The C/T boundary level in sections representing the northern Pacific paleobiogeographic province (British Columbia, Vancouver Island, California, Alaska, northeast Russia, Sichote Alin, Sakhalin Island, Kuril Islands, Japan) is generally characterised by a c. 30–50 m thick sequence of interbedded sandstone and shale facies with an unfossiliferous interval at the boundary level, followed by the first appearance of a Turonian fauna in the overlying mudstone or siltstone lithofacies (see, e.g., Haggart 1986 and references therein). The section in the central part of Hokkaido is a good example of such a succession: the so-called "black shale" interval is almost 50 m thick there and contains only small-sized ichnofossils (*Planolites* and *Chondrites*) that are indicative of an oxygen-poor depositional setting (Hayakawa 2001). The C/T boundary is provisionally placed within this unfossiliferous, black shale interval; a Turonian fauna has been recorded from above it, in dark grey mudstone layers with muddy turbidites (Toshimitsu et al. 1995). This succession is similar to that in Sakhalin, which is in the same paleobasin and biotic province.

In Sakhalin, C–T successions are distributed mainly in the southern and central part of the island (Fig. 1). Detailed macrofaunal and microfaunal analyses of the boundary interval were carried out in southern Sakhalin at the reference section in the River Naiba valley (Poyarkova 1987). This is the most complete section available (Fig. 2) and forms the basis for the present study. Eighteen additional sections are distributed over the island (Fig. 1). Generally, the River Naiba valley succession represents a sublittoral setting with extremely high sedimentation rates of up to 190 m/m.y. (Alabushev 1995). The thickness of the C–T succession exposed here is c. 600 m. In Hokkaido, Okada (1997) also recorded high rates of clastic sedimentation (>185 m/m.y.) during a sea-level highstand during the late Cenomanian to early Turonian (Middle Yezo Group), reflecting tectonic uplift and highly active magmatism.

The Naiba C–T sequence comprises typically monotonous, rhythmic alternations of mudstones with thin (10–20 cm) intercalations of siltstone, sandstone, tuffaceous sandstones, and sporadic marly concretions containing numerous fossils. There is no evidence for a hiatus or an unconformity at the stage boundary level here (Fig. 3). The Cenomanian interval extends from Member 3 of the Naiba Formation up to the top of Member 2 of the Bykov Formation. The light-grey sandstone at the top of Member 2 of the Bykov Formation has yielded much plant debris and numerous marly fossiliferous concretions with a marine Cenomanian macrofauna; these beds were referred to as "debris sandstone" by Zonova et al. (1993). Members 3–6 of the Bykov Formation have been dated as Turonian (Poyarkova 1987). Previously, the C/T boundary was placed just above the "debris sandstone" at the lower limit of Member 3 of the Bykov Formation (Poyarkova 1987; Zonova et al. 1993). Member 3 comprises mudstones interbedded with black, grey and green tuffaceous sandstones and siltstones and bentonitic clay, reflecting shallow-water settings and strong volcanic activity. That "coloured" interval is barren of any fossils and is generally 40–50 m thick (Fig. 3). The first appearance of a Turonian fauna has been recorded in the black mudstones just above the coloured barren interval (Fig. 4). Member 3 is a useful marker horizon because of its distinctive features. In the River Naiba valley, Member 3 is best exposed at locality 139 and it can be traced easily for c. 7 km along the valley (Fig. 2). In the West Sakhalin Mountains (e.g., at Zhonkier Cape (Fig. 1, section 19), Hoj Cape (section 18), and Verblud Mount (section 16)), this interval is also well exposed and reaches a thickness of 30–50 m. Moreover, in 1986, Zonova and Yazykova observed the same lithological features at the C/T boundary in the River Kelinejveem (River Velikaja valley) in northeastern Russia. The thickness of this coloured barren interval does not exceed 50 m there, but colours differ and are brighter, maybe due to the dominance of siltstone lithofacies in comparison to Sakhalin.

In summary, the C–T interval in Sakhalin comprises an apparently uninterrupted succession from relatively deep marine, offshore mudstones representing an open shelf to sandstones of a shelf-slope basin, with a maximum transgression in the early Turonian but a short episode of relatively shallow water across the C/T boundary. The tuffaceous debris sandstone in the upper Cenomanian and bentonitic clay interlayers in Member 3 of the Bykov Formation, as well as the light-grey muddy turbidites in the lower Turonian, are evidence of abrupt volcanic and tectonic activity. Plate movements and magmatism in the northern Pacific were extremely active during Cretaceous time (Filatova 1995, 1998). Major tectonic belts run parallel to the distribution
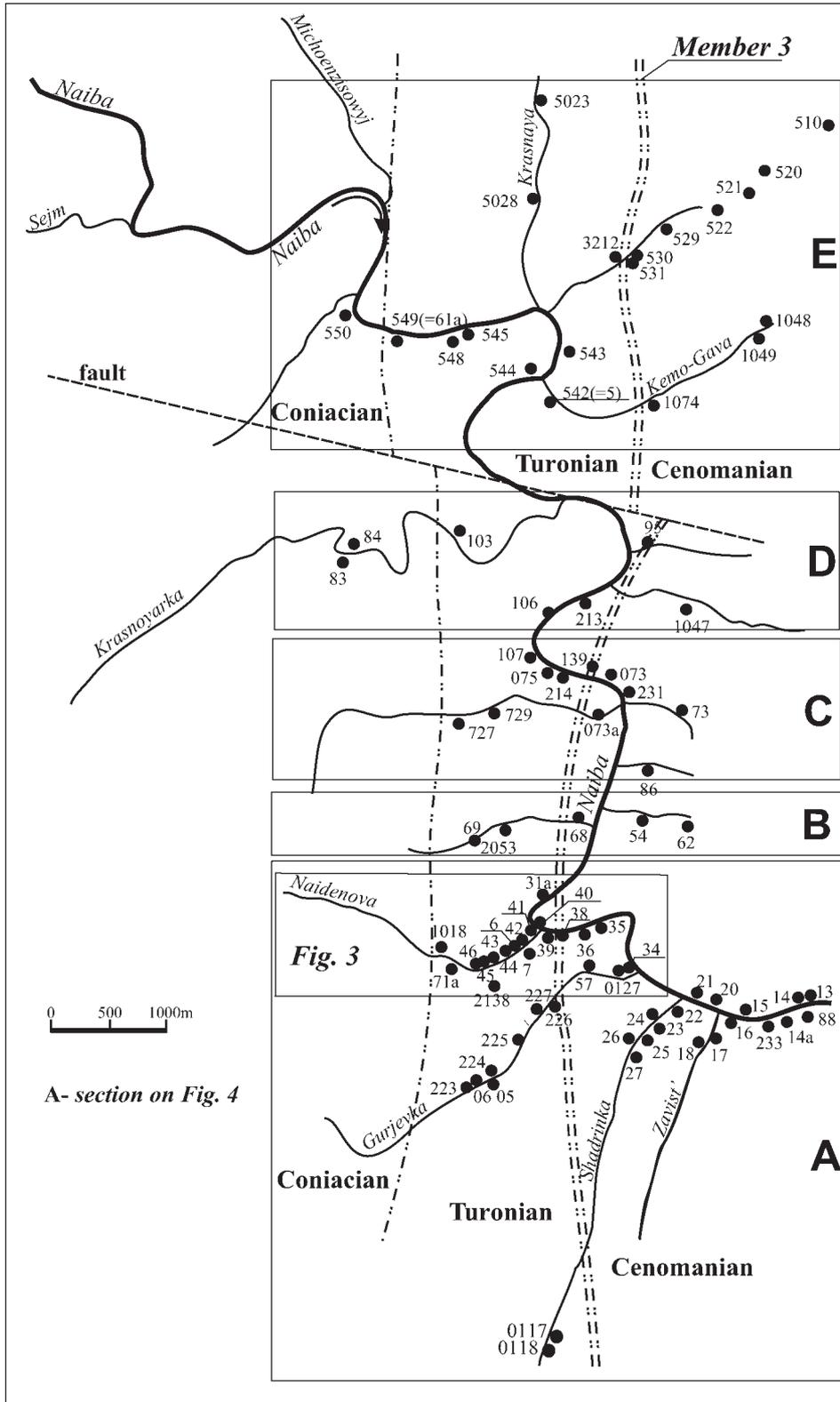
Fig. 2 Locations of sample outcrops of Upper Cretaceous deposits in the River Naiba valley. A–E refer to the correlated stratigraphic sections shown in Fig. 4.

of volcanic and plutonic rocks from the Guangxi region in southeast China to the Chukotka in eastern Russia, extending over 7000 km along the eastern continental margin (Okada 1999). A similar, short-lived impulse of shallowing in the latest Cenomanian has been noted in different sections during a general interval of sea-level highstand (Vejmarn et al. 1998).

Studies of the mineralogical composition of the Naiba reference section deposits (Poyarkova 1987) have shown that the boundary between two mineralogical zones, namely the titanite-epidote zone and the garnet-zircon zone within the heavy mineral tourmaline-garnet-zircon fraction, occurs just below the "coloured barren interval". Generally, the heavy
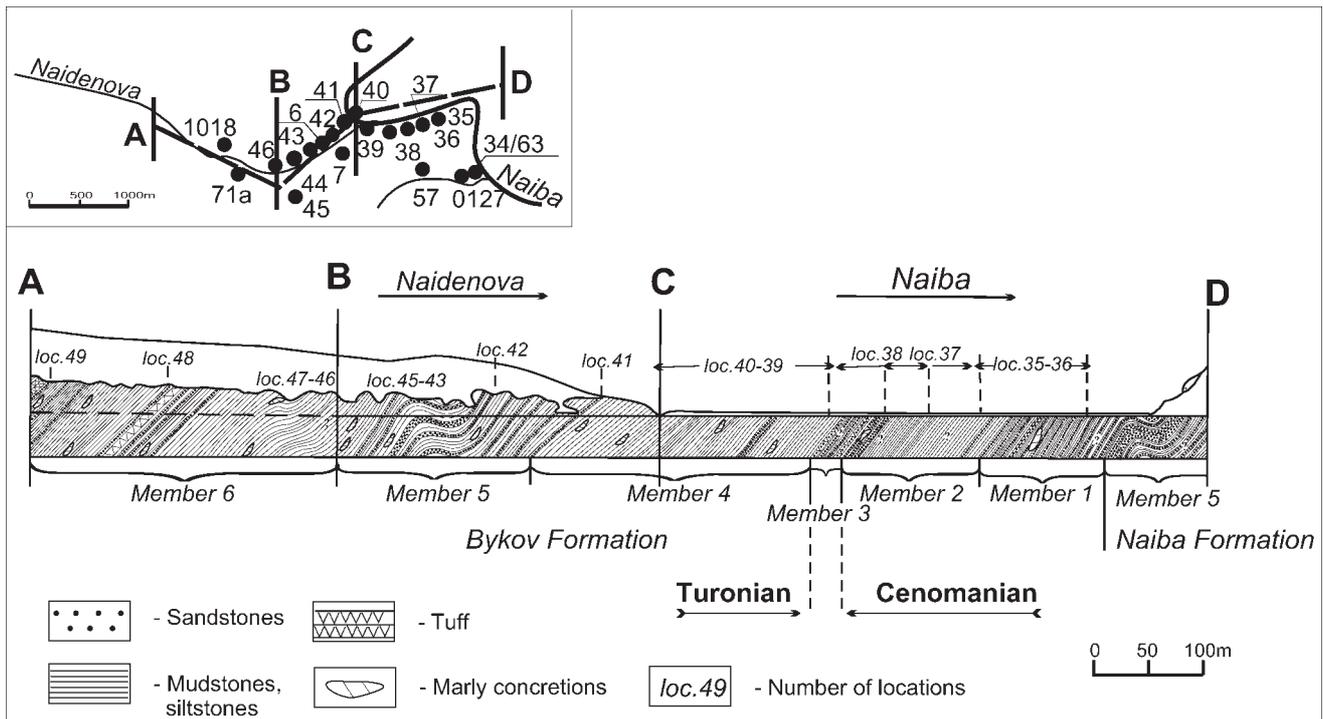
Fig. 3 Cenomanian–Turonian lithologic section in the River Naiba valley, at the Naidenova/Naiba confluence.

mineral fraction dominates in the Turonian up to the Maastrichtian, whereas minerals of the light fraction prevail in Albian–Cenomanian deposits. Moreover, high percentages of tourmaline (10%), zircon (60%), and titanite (15%) are recorded from Member 3 (Bykov Formation). This abrupt change of the mineralogical composition and the high amounts of some minerals at this level also demonstrate that some tectonic activity must have taken place in the Sakhalin paleobasin at this level.

BIOSTRATIGRAPHY

Ammonites

The succession of C–T ammonite assemblages identified in Sakhalin has enabled the establishment of 10 zones (5 zones in the Cenomanian and 5 in the Turonian), based on first occurrences (FO) of zonal indices (Fig. 5) and elaboration of the stratigraphic ranges of other key species (Fig. 6). Material collected from the River Naiba valley presents a rich record of fairly well preserved specimens (Fig. 7–10), which allow recognition of the C/T boundary. Most of the zones have already been described in detail in previous papers (Zonova et al. 1993; Zonova & Yazykova 1998).

In comparison with the Turonian, the Cenomanian interval in Sakhalin Island generally presents a rather less taxonomically diverse record of ammonites. Four ammonite zones have previously been described by Yazykova (in Zonova et al. 1993), namely those of *Desmoceras* (*Desmoceras*) *kossmati*, *Mantelliceras* sp., *Calycoceras* sp., and *Desmoceras* (*Pseudouhligella*) *japonicum*. A fifth zone, that of *Acanthoceras sussexiense*, is proposed here. In total, the Sakhalin sections have yielded 15 Cenomanian ammonite

species, representing 13 genera and 7 families. The Acanthoceratidae and Gaudryceratidae dominate, with the former represented by three cosmopolitan taxa, and the latter by four typical Cenomanian species. The remaining ammonites represent one species of the families Turrilitidae, Puzosiidae, and Phylloceratidae, and two species each of the Kossmaticeratidae and Desmoceratidae.

The *Desmoceras* (*Desmoceras*) *kossmati* Zone yields *D.* (*Desmoceras*), *D.* (*Pseudouhligella*), *Parajaubertella*, *Zelandites*, *Neophylloceras*, and *Anagaudryceras* (Fig. 6). Traditionally, the first appearance of *Parajaubertella kawakitana* (Fig. 7.1,2) has been taken to define the base of the Cenomanian in Far East Russia (Poyarkova 1987; Zonova et al. 1993; Alabushev & Wiedmann 1997). The *Mantelliceras* sp. Zone is characterised by first representatives of the genus *Mantelliceras*, a typical Cenomanian taxon known from many regions in the world (Tröger & Kennedy 1996), and comparatively long ranging *Zelandites inflatus* and *Anagaudryceras buddha.* The latter species was first described from the Cenomanian of India (Forbes 1846).

Following Tröger & Kennedy (1996), the first appearance of a representative of the genus *Acanthoceras* is taken as a criterion for recognition of the base of the middle Cenomanian. Thus, the lower/middle Cenomanian boundary in Sakhalin is situated at the base of the *Acanthoceras sussexiense* Zone (Fig. 5, 6).

The lowest occurrence of *Calycoceras* is one of several possible criteria for recognition of the upper Cenomanian. However, a definition for the base of the substage was not agreed in 1995 (Tröger & Kennedy 1996). The *Calycoceras* sp. Zone, established in Sakhalin by Yazykova (in Atabekian et al. 1991), yields *Calycoceras*, *Gaudryceras*, *Neophylloceras*, *Parajaubertella*, *Mikasaites*, and *Turrilites*
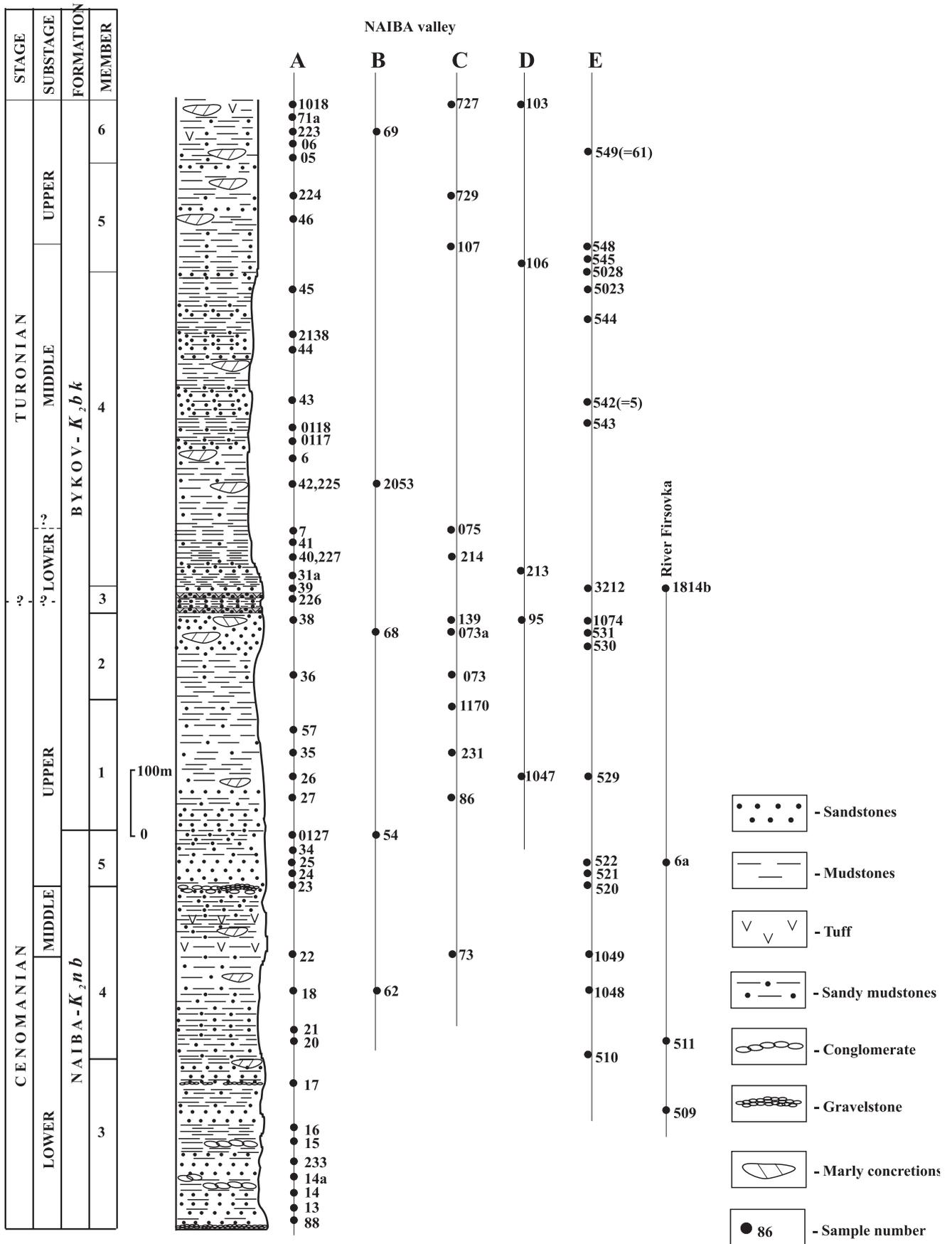
Fig. 4 Cenomanian–Turonian stratigraphic section in the River Naiba valley.

Series	Stage	substage	Formation	member	Ammonite Zone Yazykova in Zonova et al, 1993, this paper	Inoceramid Zone Zonova in Zonova et al, 1993, this paper		Radiolarian Zones Kazintsova, 2000	Foraminifera Zones Turenko in Poyarkova, 1987
UPPER CRETACEOUS	Con.	l. / m.	Bykov	6	Jimboiceras mihoense	Inoceramus uwajimensis		Orbiculiforma quadrata - O. monticelloensis	Planulina rumoiensis-Globotruncana japonica
	Turonian	upper		5	Jimboiceras planulatiforme / Subprionocyclus sp.	Mytiloides incertus-Inoceramus teshioensis			Silicosigmoilina futabaensis-Rzehakina subcircularis
		middle		4	Scaphites planus / Romaniceras (Yubariceras) ornatissimum	Inoceramus hobetsensis-I. iburiensis		Crucella cachensis - Alievium superbum	
		low.			Fagesia sp.	Mytiloides aff. labiatus			
	?			3	?	?		?	?
	Cenomanian	upper		2	Desmoceras (Pseudouhligella) japonicum	Inoceramus aff. tenuis	Actinoceramus nipponicus	Haliomma sachalinica - Dictiomita multicostata	Glomospira corona-Ammobaculites gratus
			Naiba	1 / 5	Calycoceras sp.	Inoceramus pressulus-I. gradilis		Lipmanium sacra - mentoensis - Archaeodictyomitra squinaboli	
		middle		4	Acanthoceras rhotomagense / Mantelliceras sp.				
		lower		3	Desmoceras (D.)kossmati	Inoceramus aff. crippsii			

[____] - data gap   [- - ? - -] - unfossiliferous interval
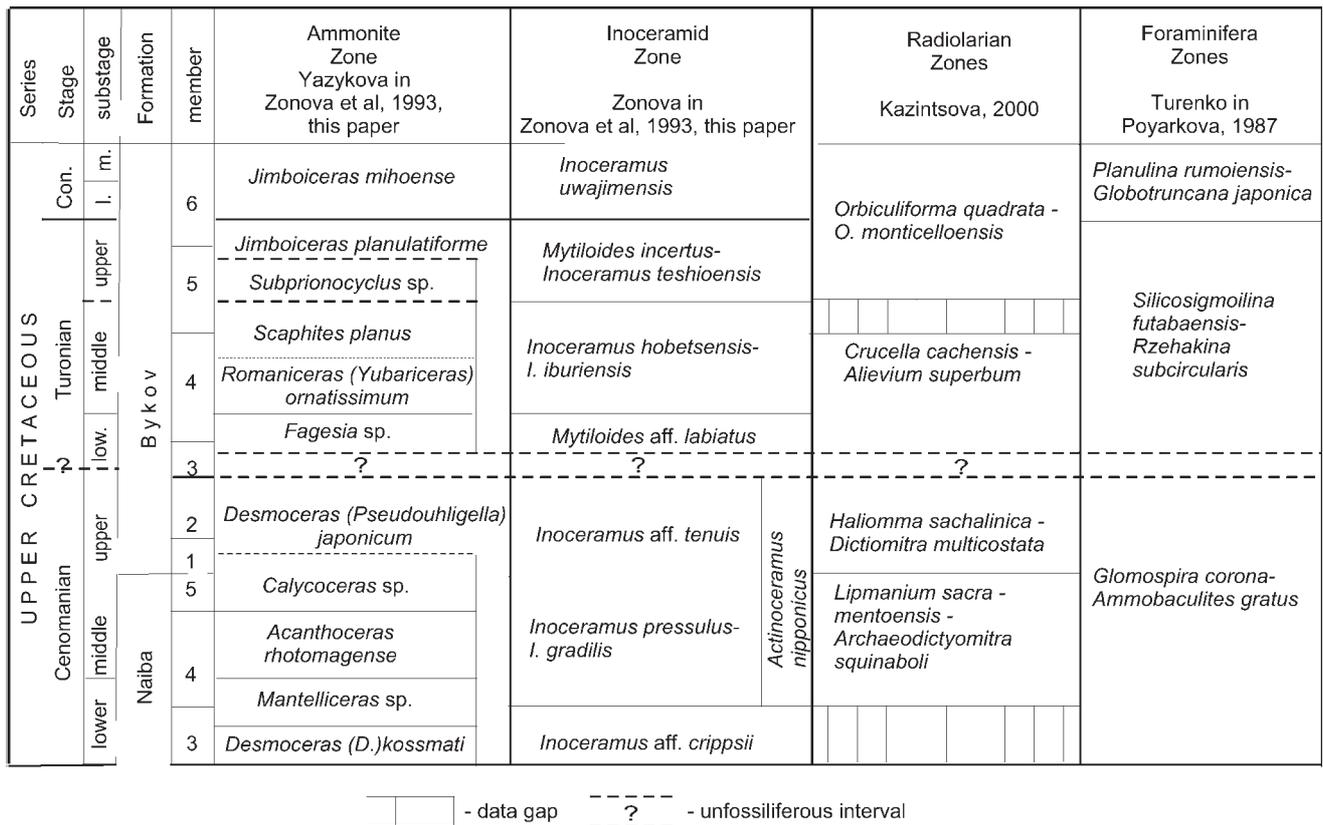
Fig. 5 Ammonite, inoceramid, radiolarian, and foraminiferal zonations of the Cenomanian–Turonian in Sakhalin Island.

(Fig. 6). For the time being, the middle/upper Cenomanian boundary in Sakhalin is placed at the FO of *Calycoceras*.

The *Desmoceras (Pseudouhligella) japonicum* Zone is dated as Cenomanian, the zonal species being widely distributed throughout this stage in the Pacific Realm (Vereschagin et al. 1965; Zonova et al. 1993; Toshimitsu et al. 1995).

All Cenomanian ammonite species disappeared at the C/T boundary. Not one representative of the genera *Mantelliceras*, *Acanthoceras*, *Mikasaites*, and *Calycoceras* is known from the Turonian of Sakhalin or from other regions of the world (Vejmarn et al. 1998).

The definition of the base of the Turonian Stage on the basis of ammonites is fraught with difficulties. Unfortunately, previous studies have not discussed this issue in detail. For instance, Alabushev (in Alabushev & Wiedmann 1997) proposed the *Romaniceras (Yubariceras) ornatissimum* Zone as the lowest Turonian zone, but Poyarkova (1987) and Zonova & Yazykova (1998) demonstrated that the lowest occurrence of the Turonian ammonites *Fagesia* sp. and *Jimboiceras planulatiforme* (see Fig. 6) in marl concretions in the mudstones of Member 4 of the Bykov Formation, just above the "coloured barren interval", predates that of *R. (Y.) ornatissimum*.

The Turonian succession generally furnishes taxonomically more diverse ammonite assemblages than the Cenomanian, with new species and genera appearing (Fig. 6) and a marked change of shell morphotypes observed (Fig. 9, 10). Five Turonian zones have been recognised (Fig. 5), namely those of *Fagesia* sp., *Romaniceras (Yubariceras) ornatissimum*, *Scaphites planus*, *Subprionocyclus* sp., and *Jimboiceras planulatiforme* (Zonova et al. 1993; Zonova & Yazykova 1998). In total, 21 species, representing 16 genera and 10 families, have been identified from the Turonian of Sakhalin. The number of heteromorph ammonites is relatively high compared to the Cenomanian (only *Turrilites costatus*), with six genera (in three families) represented.

The occurrence of representatives of the genus *Fagesia* is typical of the base of the Turonian Stage in many regions in the world (e.g., Collignon 1965; Freund & Raab 1969; Khakimov 1970; Chancellor et al. 1994, amongst others). In Sakhalin (Fig. 8), this taxon co-occurs with *Jimboiceras planulatiforme* (Fig. 10), a widely distributed species in the Turonian of the northern Pacific subprovince (Matsumoto 1959a,b, 1988; Zonova & Yazykova 1998) and of Madagascar (Collignon 1961, 1965). The FO of *Jimboiceras planulatiforme* and the genus *Fagesia* are the main criteria for recognition of the lower boundary of the Turonian in Far East Russia (Zonova & Yazykova 1998). This is in contrast with data provided by Alabushev (in Alabushev & Wiedmann 1997, p. 4), who considered the *J. planulatiforme* Zone to be of middle–late Turonian age.

The survival interval in ammonite evolution following the C/T boundary extinction equates with the *Fagesia* sp. Zone. During that time, long-lived genera of the families Gaudryceratidae (*Gaudryceras* and *Zelandites*) and Phylloceratidae (*Neophylloceras*) persisted and representatives of *Fagesia* and *Nipponites* appeared (Fig. 6). The genera *Gaudryceras*, *Zelandites*, and *Neophylloceras* are conservative lineages that continued up into the Maastrichtian; *Fagesia* disappeared at the end of the Turonian, while the last *Nipponites* occurred in the lower Coniacian.
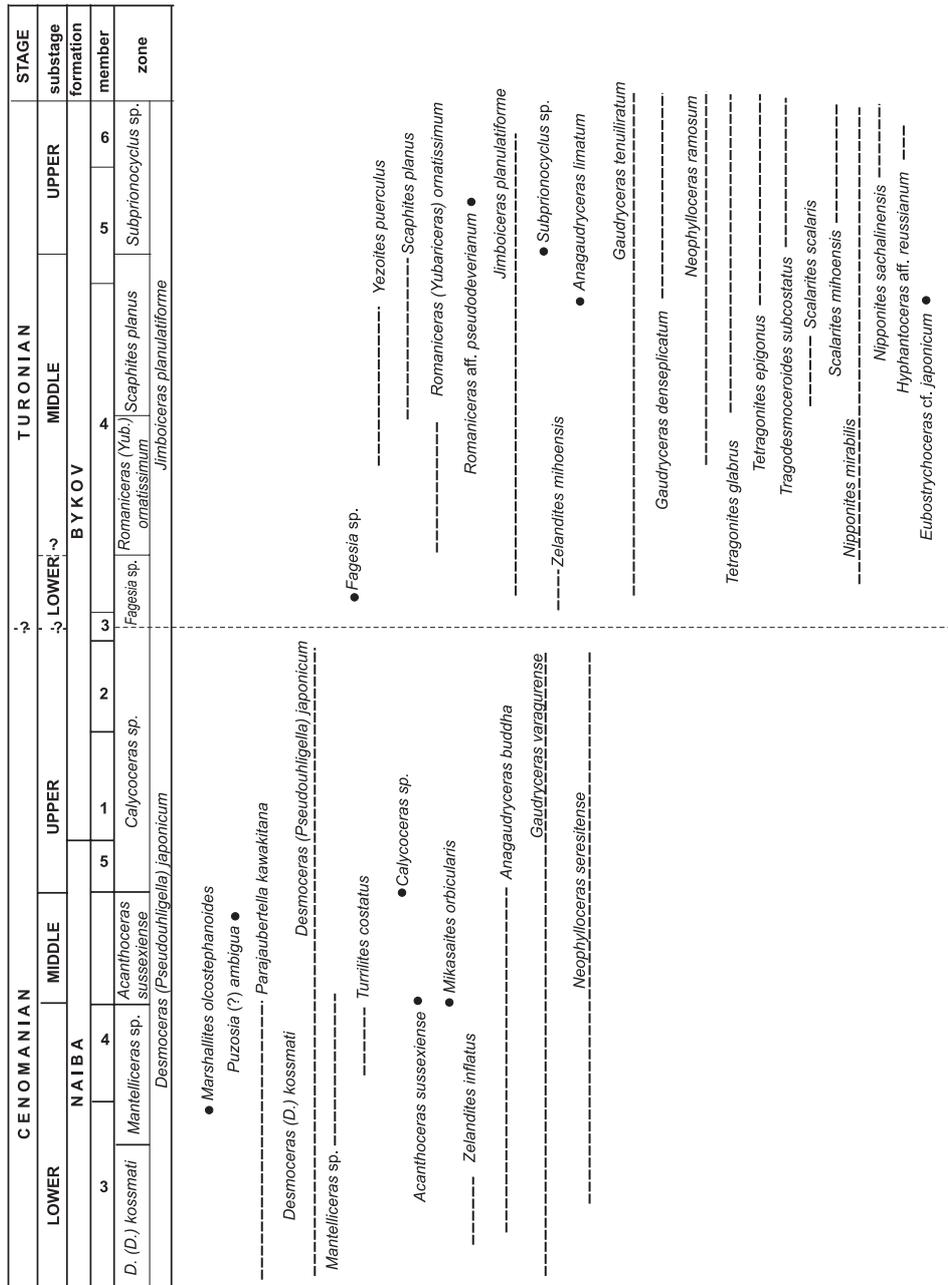
The recovery interval corresponds to the *Romaniceras* (*Yubariceras*) *ornatissimum* Zone, which allows correlation with the European and Mediterranean realms based on the distribution of the zonal species. According to Küchler (1998) and Wiese & Wilmsen (1999), the *Romaniceras* (*Yubariceras*) *ornatissimum* Zone is placed within the middle Turonian of Spain. It is difficult to establish the lower/middle Turonian boundary in Sakhalin, where the stratigraphically lowest specimens of the index taxon are from locality 31a (Fig. 2, 6). Thus, the lower/middle Turonian boundary in Sakhalin would seem to correspond to the base of the *R.* (*Y.*) *ornatissimum* Zone (Fig. 5).

The *Scaphites planus* Zone (upper middle Turonian, see Fig. 5) is the time of radiation and maximum diversity of Turonian ammonites in Sakhalin and in the northeastern regions of Russia (Vereschagin et al. 1965; Alabushev &

Fig. 7 Some representatives of the Cenomanian ammonites from Sakhalin. **1, 2** *Parajaubertella kawakitana* Matsumoto: 1a–d, N7/12769; 2a–c, N8/12769, lower Cenomanian, *Mantelliceras* sp. Zone, River Susuja, loc. 73. **3, 4** *Neophylloceras seresitense* (Pervinquière): 3, N5/12769; 4, N4/12769, upper Cenomanian, *Desmoceras* (*Pseudouhligella*) *japonicum* Zone, River Aj, loc. 29, loc. 15. **5**, *Gaudryceras* cf. *varagurense* Kossmat, N6/12769, lower Cenomanian, *Desmoceras* (*D.*) *kossmati* Zone, River Aj, loc. 233. **6**, *Zelandites inflatus* Matsumoto, N1/12769, lower Cenomanian, *Desmoceras* (*D.*) *kossmati* Zone, River Juzhnaya Hondasa, loc. 1495. **7**, *Anagaudryceras* cf. *buddha* (Forbes), N3/12769, upper Cenomanian, *Desmoceras* (*Pseudouhligella*) *japonicum* Zone, River Aj, loc. 29. **8a,b** *Marshallites olcostephanoides*, lower Cenomanian, *Mantelliceras* sp. Zone, River Nayba, loc. 18. **9a,b** *Mantelliceras* sp., N2/12769, lower Cenomanian, *Mantelliceras* sp. Zone, River Firsovka, loc. 509. All figures ×1.2.
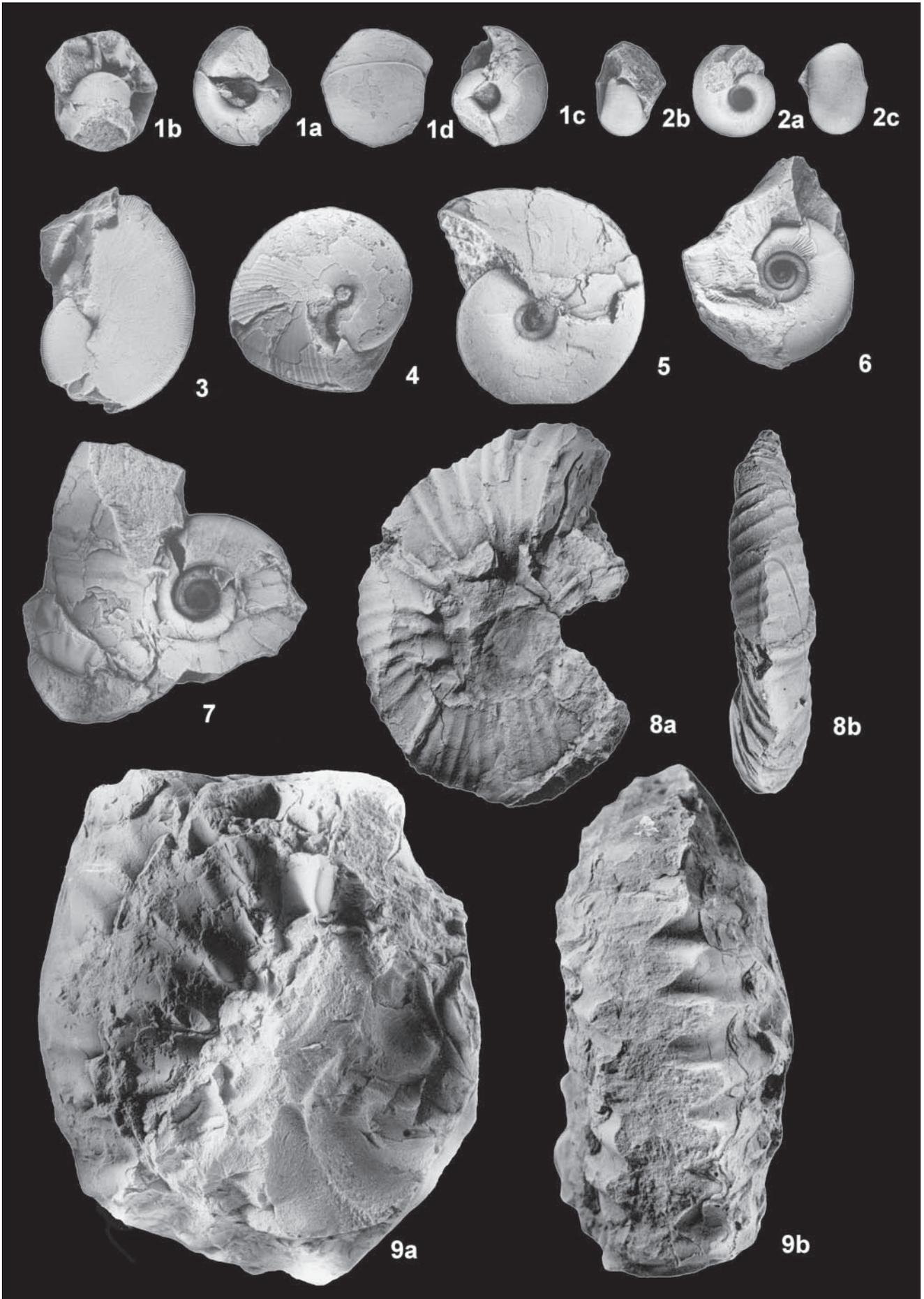
Fig. 8   1, *Mantelliceras* sp. N9/12769, lower Cenomanian, *Mantelliceras* sp. Zone, River Firsovka, loc. 511. ×0.61.

Wiedmann 1997; Zonova & Yazykova 1998). This typical scaphitid facies is easily traced from the northeast through Sakhalin to Hokkaido (Tanabe 1979); additional new genera and species appeared during this time (Fig. 6).

Locally, the middle/upper Turonian boundary has been established by the FO of *Subprionocyclus* sp. (= base of the *Subprionocyclus* sp. Zone; within Member 5 of the Bykov Formation, see Fig. 5). The same pattern has been reported from Japan (Toshimitsu et al. 1995) and Spain (Küchler 1998; Wiese & Wilmsen 1999). At present, there are no other cosmopolitan taxa of typically late Turonian age known from this level. This time interval is characterised by a relative stability in ammonite evolution. The total number of species decreased slightly and new taxa appeared gradually (Fig. 6).

The *Jimboiceras planulatiforme* Zone was described in detail in previous works (Matsumoto 1959c; Zonova et al. 1993; Zonova & Yazykova 1998), to which reference is made.

Generally, taxonomic diversity patterns in the post-crisis Turonian ammonite fauna in Sakhalin reflect a sequence of phases (Kauffman & Erwin 1995; Harries & Little 1999). At first there was a mass extinction at the C/T boundary followed by a survival interval (the *Fagesia* sp. Zone) with long-lived conservative genera and two new genera. The appearance of numerous new taxa indicates the recovery phase (*Romaniceras* (*Yubariceras*) *ornatissimum* Zone) and the acme of ammonites (the *Scaphites planus* Zone), and continues the relatively stable phase (i.e., nomismogenesis (*sensu* Kauffman 1985)) prior to another faunal turnover at the Turonian/Coniacian boundary (Zonova & Yazykova 1998).

Inoceramids

The succession of C–T inoceramid assemblages identified in Sakhalin has enabled the establishment of seven zones (four zones in the Cenomanian and three in the Turonian;

Fig. 9 Some representatives of the Turonian ammonites from Sakhalin. **1a,b** *Fagesia* sp., lower Turonian, *Fagesia* sp. Zone, River Firsovka, loc. 1814b. **2–6** *Scaphites* cf. *planus* (Yabe): middle Turonian, *Scaphites planus* Zone: 2–5, River Lobanovka, loc. 3812-1, 6, River Nayba, loc. 41. **7**, *Tetragonites* cf. *epigonus* (Kossmat), middle Turonian, *Scaphites planus* Zone, River Nayba, loc. 41. **8a,b** *Gaudryceras tenuiliratum* (Yabe), middle Turonian, *Scaphites planus* Zone, River Naiba, loc. 213. **9a,b** *Eubostrychoceras* cf. *japonicum* (Yabe), middle Turonian, *Scaphites planus* Zone, River Naiba, loc. 214. **10a–c** *Anagaudryceras limatum* (Yabe), middle Turonian, *Scaphites planus* Zone, River Naiba, loc. 41. All figures ×1.2.

Fig. 10 Some representatives of the Turonian ammonites from Sakhalin. **1, 3** *Nipponites mirabilis* Yabe: 1a–c upper Turonian, *Subprionocyclus* sp. Zone, River Onorka, loc. 547a; 3a–c upper Turonian, uppermost part of *Jimboiceras planulatiforme* Zone, River Krasnoyarka, loc. 103. **2**, *Jimboiceras* cf. *planulatiforme* (Jimbo), upper Turonian, *Subprionocyclus* sp./*Jimboiceras planulatiforme* Zone, River Naiba, loc. 71a. **4a–c** *Jimboiceras planulatiforme* (Jimbo). N27/12769, lower Turonian, *Fagesia* sp. Zone/*Jimboiceras planulatiforme* Zone, River Naiba, loc. 31a. All figures natural size.

Fig. 5), as based on the first occurrence of zonal index species (Fig. 11). Most of the zones have already been described in previous papers (Zonova et al. 1993; Zonova & Yazykova 1998). The inoceramid zonation correlates relatively well with those of northeast Russia and Japan and matches the ammonite, foraminifera, and radiolarian schemes well. Material collected from the River Naiba valley presents a rich record of fairly well preserved specimens (Fig. 12–15), which allow recognition of the C/T boundary. However, at present, it is impossible to determine substage boundaries within the Cenomanian in Sakhalin using inoceramid species.

The main feature of the Cenomanian inoceramid assemblage is the wide distribution of the group, which comprises species which have a thin, flat shell with weakly developed sculpture or none at all (e.g., *Inoceramus pressulus*, *I. gradilis*, *I. pennatulus*, *I. ginterensis*, and *I. reduncus*; Fig. 12, 13). The presence or absence of sculpture is not related to ontogeny (Pochialajnen 1988).

The oldest Cenomanian zone is that of *Inoceramus* aff. *crippsi*. The first specimens of the index taxon were reported from Sakhalin in the 1940s (Matsumoto 1942, 1943). Some years later, Matsumoto (1959c) established this zone but failed to provide details; its formal identification (Poyarkova 1987) and description in Sakhalin occurred much later (Zonova et al. 1993). The zonal species is well known from the Cenomanian of Tethyan areas (e.g., the Crimea and Caucasus; Pavlova 1955; Moskvin 1959), as well as from the basal Cenomanian of France (Tröger & Kennedy 1996) and the upper Cenomanian of Poland (Marcinowski 1974). In the Naiba section, *Inoceramus* aff. *crippsi* co-occurs with *Actinoceramus nipponicus* (Fig. 12) and *Inoceramus pictus* (Zonova et al. 1993). The former species is widely distributed throughout most of the Cenomanian in the entire Pacific Realm; the latter occurs in the Cenomanian of Europe and North America (Kauffman 1975). Generally, the early Cenomanian is a time of survival for inoceramids following an extinction event at the Albian/Cenomanian boundary

Fig. 11 Stratigraphic distribution of Cenomanian–Turonian inoceramid species.

(Yazykova 2004). No Albian taxa have been found in the lower Cenomanian of Sakhalin.

Most representatives of the remaining inoceramid group appeared at the end of the early Cenomanian and in the middle Cenomanian. This recovery interval, following the Albian/Cenomanian extinction of inoceramids, corresponds approximately to the *Inoceramus pressulus – I. gradilis* Zone with a radiation and maximum diversity in the *Inoceramus* aff. *tenuis* Zone. That is also the time of high abundance of the *Pergamentia* group (Zonova et al. 1993), both in species and number of individuals.

During the late Cenomanian, inoceramid diversity gradually decreased (Fig. 11). The upper part of the *Actinoceramus nipponicus* Zone, which is generally equated with the upper lower Cenomanian up to the upper Cenomanian, is characterised by a low diversity and by the disappearance of Cenomanian species. The last

representatives of Cenomanian taxa occur just below the "coloured barren interval" discussed previously.

The first Turonian inoceramids are found just above the "coloured barren interval" in the upper part of Member 3 of the Bykov Formation (Fig. 11). The Turonian succession is generally characterised by the appearance and wide distribution of representatives of a new phylogenetic group, that of *Inoceramus lamarki*, and the occurrence of the *Mytiloides* aff. *labiatus* group in many regions of the world. The *Inoceramus lamarcki* group is represented by new shell morphotypes with well-developed sculpture, which were to become dominant during the entire Turonian. The most typical representatives of these are *Inoceramus hobetsensis* and *I. iburiensis* (Fig. 14, 15).

The Turonian inoceramid assemblage is taxonomically more diverse than the Cenomanian one. Three Turonian inoceramid zones have been recognised in the River Naiba

Fig. 12 Some representatives of Cenomanian inoceramids from Sakhalin. **1, 3** *Inoceramus* aff. *tenuis* Mantell: 1, N130/10693, upper Cenomanian, *Inoceramus* aff. *tenuis* Zone, River Susuja, loc. 73; 3, N87/12765, upper Cenomanian, *Inoceramus* aff. *tenuis* Zone, River Naiba, loc. 86. **2, 4** *Actinoceramus nipponicus* (Nagao & Matsumoto): 2a–c N112/10693, upper Cenomanian, *Inoceramus* aff. *tenuis* Zone/*Actinoceramus nipponicus* Zone, River Naiba, loc. 073; 4a–c upper Cenomanian, *Inoceramus* aff. *tenuis* Zone/*Actinoceramus nipponicus* Zone, River Shadrinka, Naiba valley, loc. 24. **5**, *Inoceramus pennatulus* Pergament, N102/10693, middle Cenomanian, *Inoceramus pressulus*, *I. gradilis* Zone, River Firsovka, loc. 6a. **6a,b** *Inoceramus gradilis* Pergament, N42/12765, middle Cenomanian, *Inoceramus pressulus*, *I. gradilis* Zone, River Aj, loc. 29. All figures natural size.

Fig. 13 Some representatives of Cenomanian inoceramids from Sakhalin. **1, 5** *Inoceramus tychljawajamensis* Vereshchagin: 1, upper Cenomanian, *Inoceramus* aff. *tenuis* Zone, River Pobedinka, loc. 8246; 5, N129/10693, upper Cenomanian, *Inoceramus* aff. *tenuis* Zone, River Naiba, loc. 073. **2, 4** *Birostrina tamurai* (Matsumoto & Noda): 2a–e N70/12765, middle Cenomanian, *Inoceramus pressulus*, *I. gradilis* Zone, River Kemo-Gava, Naiba valley, loc. 1074; 4, N72/12765, middle Cenomanian, *Inoceramus pressulus, I. gradilis* Zone, River Shadrinka, Naiba valley, loc. 27. **3a,b** *Inoceramus gradilis* Pergament, middle Cenomanian, *Inoceramus pressulus*, *I. gradilis* Zone, River Shadrinka, Naiba valley, loc. 27. **6**, *Inoceramus pressulus* Zonova, N1/10841, middle Cenomanian, *Inoceramus pressulus*, *I. gradilis* Zone, River Gurjevka, Naiba valley, loc. 0127. All figures natural size.
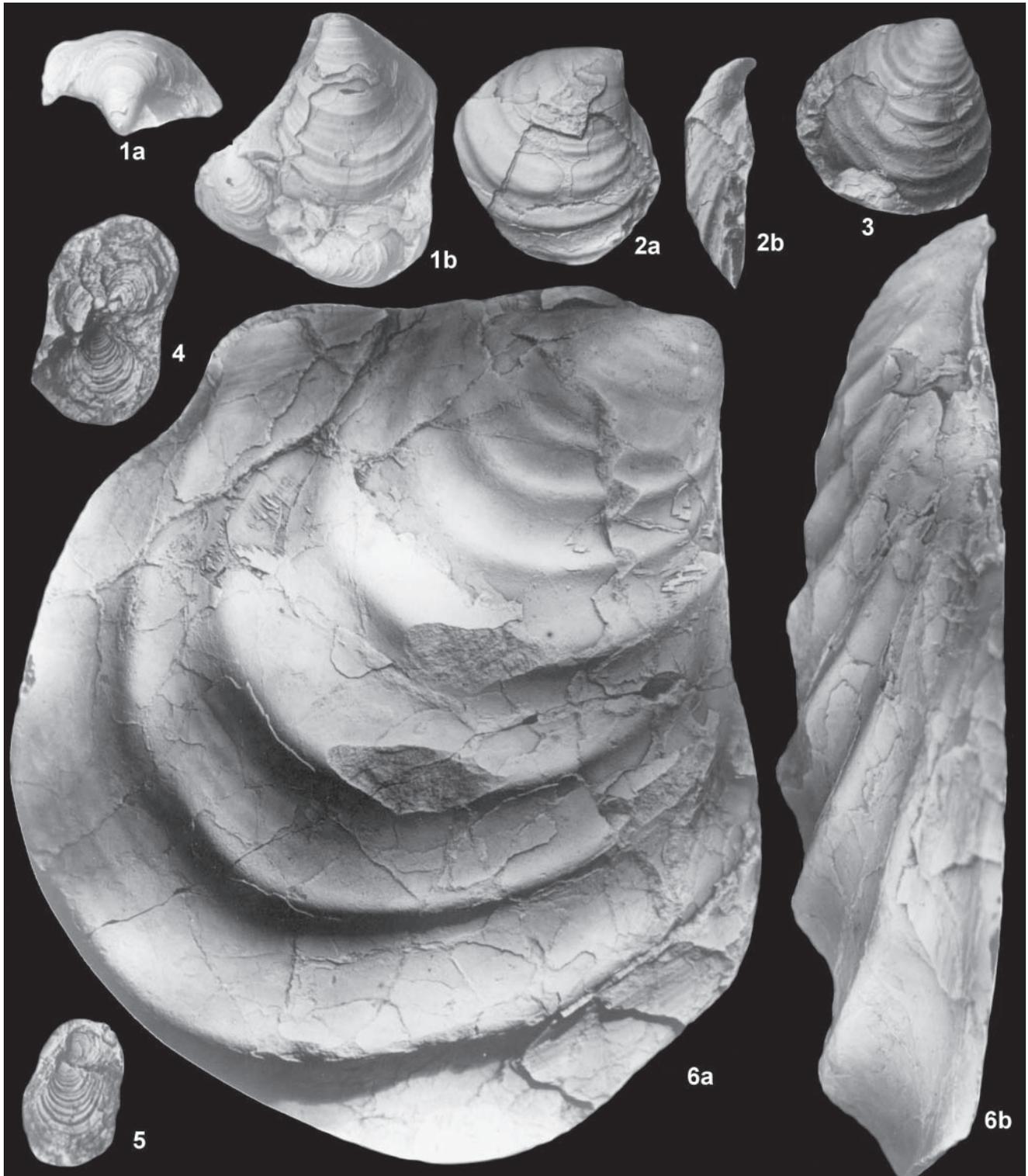
Fig. 14 Some representatives of Turonian inoceramids from Sakhalin. **1–3** *Inoceramus teshioensis* Nagao & Matsumoto: 1a,b N194/10693, upper Turonian, *Mytiloides incertus*, *Inoceramus teshioensis* Zone, River Naiba valley, River Kuma, loc. 729; 2a,b N191/10693, upper Turonian, *Mytiloides incertus*, *Inoceramus teshioensis* Zone, River Naiba valley, River Naidenova, loc. 46; 3, N193/10693, upper Turonian, *Mytiloides incertus*, *Inoceramus teshioensis* Zone, River Naiba valley, River Kuma, loc. 729. **4, 5** *Inoceramus* sp. aff. *I. teraokai* Noda: 4, N189/10693; 5, N190/10693, upper Turonian, *Mytiloides incertus*, *Inoceramus teshioensis* Zone, River Naiba valley, River Naidenova, loc. 46. **6a,b** *Inoceramus hobetsensis* Nagao & Matsumoto, N156/10693, middle Turonian, *Inoceramus hobetsensis*, *I. iburienis* Zone, River Naiba valley, River Naidenova, loc. 41. All figures natural size.
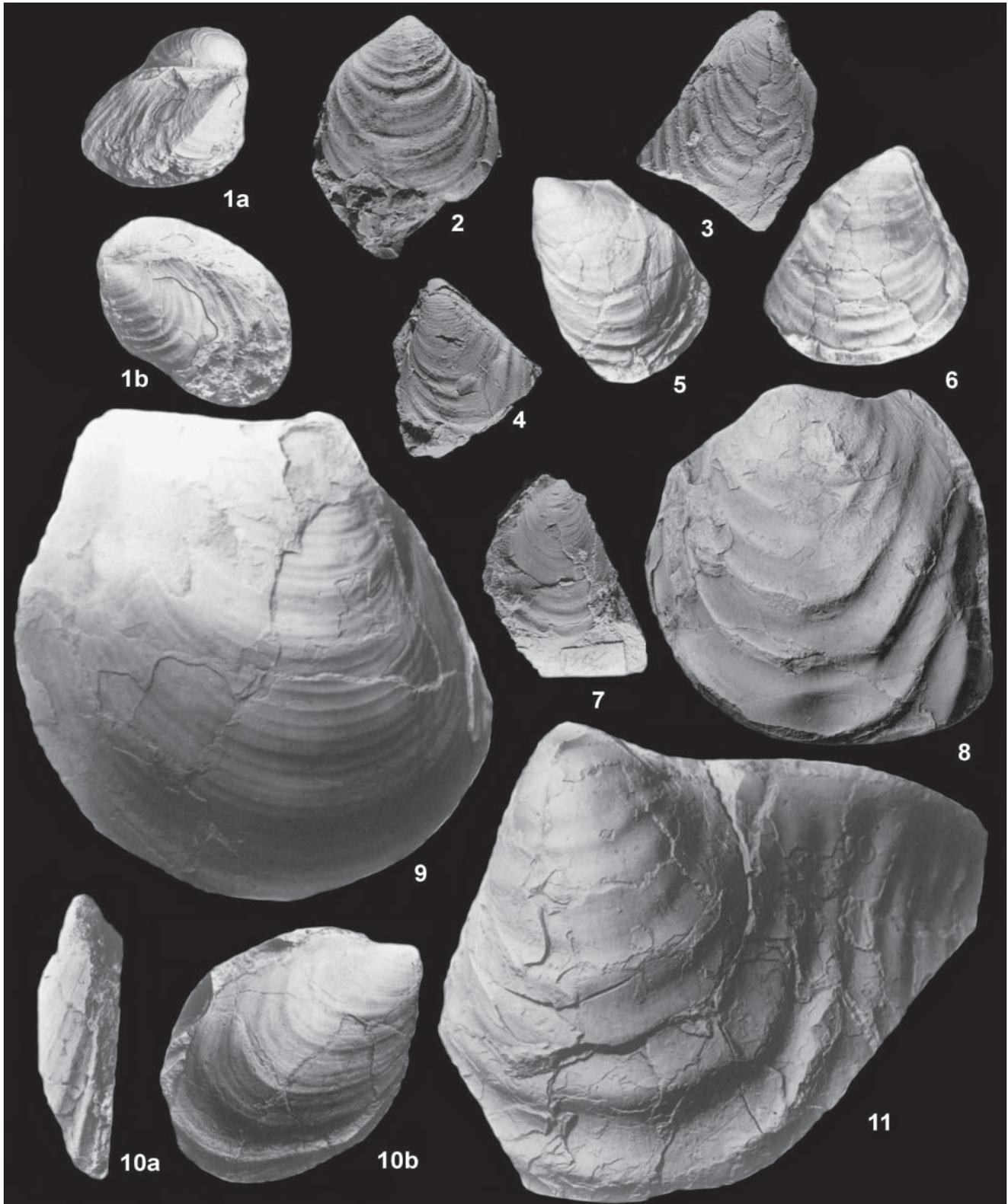
Fig. 15 Some representatives of Turonian inoceramids from Sakhalin. **1, 3–5, 7, 10** *Mytiloides* aff. *labiatus* (Schlötheim): 1a,b N176/10693; 5, N173/10693, lower Turonian, *Mytiloides* aff. *labiatus* Zone, River Naiba valley, River Gurjevka, loc. 227; 3, N96/12765; 4, N98/12765; 7, N97/12765, lower Turonian, *Mytiloides* aff. *labiatus* Zone, River Naiba, loc. 46; 10a,b N171/10693, middle Turonian, *Inoceramus hobetsensis*, *I. iburiensis* Zone, River Naiba valley, River Naidenova, loc. 42. **2**, *Inoceramus* aff. *multiformis* Pergament, N46/12580, upper Turonian, *Mytiloides incertus*, *Inoceramus teshioensis* Zone, River Naiba valley, River Shadrinka, loc. 26. **6**, *Actinoceramus costatus* (Nagao & Matsumoto), N201/10693, middle Turonian, *Inoceramus hobetsensis*, *I. iburiensis* Zone, River Naiba, loc. 5. **8**, *Inoceramus hobetsensis* Nagao & Matsumoto, N368/12765, middle Turonian, *Inoceramus hobetsensis*, *I. iburiensis* Zone, River Naiba valley, River Naidenova, loc. 41. **9**, *Inoceramus pseudocuvieri* Pergament, N168/10693, middle Turonian, *Inoceramus hobetsensis*, *I. iburiensis* Zone, River Naiba, loc. 213. **11**, *Inoceramus* sp. aff. *I. iburiensis* Nagao & Matsumoto, N232/10693, middle Turonian, *Inoceramus hobetsensis*, *I. iburiensis* Zone, River Naiba, loc. 106. All figures natural size.

section in Sakhalin (Fig. 5), namely those of *Mytiloides* aff. *labiatus* (lower Turonian), *Inoceramus hobetsensis – I. iburiensis* (middle Turonian to lower upper Turonian), and *Mytiloides incertus – Inoceramus teshioensis* (upper Turonian). All three zones have been described in detail and recorded from the entire Pacific Realm (see Poyarkova 1987; Zonova et al. 1993; Zonova & Yazykova 1998). In total, 17 species, representing 2 genera, were identified from the Turonian of Sakhalin, although at the genus level the taxonomy of inoceramids is far from resolved.

Generally, taxonomic diversity patterns in the post-crisis Turonian inoceramid fauna in Sakhalin show a sequence of phases (Kauffman & Erwin 1995; Harries & Little 1999). Following upon the mass extinction at the C/T boundary is a survival interval (the *Mytiloides* aff. *labiatus* Zone) with low diversity (only three new species). The subsequent appearance of new taxa indicates the recovery phase and radiation (the *Inoceramus hobetsensis – I. iburiensis* Zone), and continues the phase of nomismogenesis (the *Mytiloides incertus – Inoceramus teshioensis* Zone) prior to a new faunal turnover at the Turonian/Coniacian boundary (Zonova & Yazykova 1998).

Foraminifera

Foraminifera from the upper part of the Naiba and Bykov Formations have been studied previously by Turenko (in Poyarkova 1987), who recorded poor to moderately diverse assemblages from this interval, composed mostly of benthic forms, although the Bykov Formation (Fig. 16) did yield a few planktonic species as well. A distinctive portion of the assemblages is composed of siliceous-agglutinated taxa (*Bathysiphon*, *Hyperammina*, *Ammobaculites*, *Saccamina*, *Glomospira*, *Ammodiscus*, *Haplophragmoides*, *Asanospira*, *Rzehakina*, *Silicosigmoilina*, and *Reophax*). Calcareous benthic species are represented mainly by nodosariids (*Lenticulina*, *Astacolus*, *Marginulina*, *Saracenaria*, *Dentalina*, and *Hemirobulina*), while gavelinellids occur in varying proportions. Planktonic faunas consist predominantly of long-ranging, non-keeled species, identified by Turenko as *Whiteinella brittonensis* (Loeblich and Tappan), *W. portsdownensis* (Williams-Mitchell), *W.* sp., *Hedbergella delrioensis* (Carsey), *H. planispira* (Tappan), and *H.* sp. These species are known to have their lowest stratigraphical occurrences in the upper Cenomanian and highest in the Santonian. Keeled forms identified by Turenko (in Poyarkova 1987, fig. 23) as *Marginotruncana marginata* (Reuss), *M.* sp., and *Archaeoglobigerina cretacea* (d'Orbigny), appear in the upper part of the Bykov Formation. Worldwide, *M. marginata* (Reuss) is recorded from the upper Turonian to the upper Santonian, while *A. cretacea* ranges from the upper Turonian to the Maastrichtian.

The interval studied by us was divided into two foraminiferal zones by Turenko (in Poyarkova 1987) (Fig. 5), viz, the *Glomospira corona – Ammobaculites gratus* Assemblage Zone and *Silicosigmoilina futabensis – Rzehakina subcircularis* Assemblage Zone. Planktonic foraminifera, occurring sporadically and represented by species of low stratigraphic value, cannot serve as a basis for distinguishing planktonic foraminiferal zones in the Naiba and Bykov Formations. This means that it is impossible to correlate this section directly by means of foraminifera with sections in Japan where planktonic foraminiferal zonations have been established (Toshimitsu & Maiya 1986; Toshimitsu et al. 1995).

For the purpose of the present study, >50 samples were processed, but unfortunately most of them turned out to be unproductive. Kodama et al. (2000) were also unsuccessful in extracting foraminifera and calcareous nannoplankton in the upper part of the Bykov Formation and the overlying Krasnoyarka Formation. The only interval from which foraminifera have been recorded in the present study is Member 4 of the Naiba Formation (Fig. 16). Foraminiferal assemblages are dominated by organic-cemented siliceous agglutinated taxa including *Bathysiphon*, *Rhabdammina*, *Hyperammina*, *Saccammina*, *Glomospira*, *Ammodiscus*, *Haplophragmoides*, and *Asanospira*. A few calcareous taxa, including *Quadrimorphina*, *Lenticulina*, *Astacolus*, and ?*Valvulineria*, occur sporadically. Tubular forms, not illustrated by Turenko (in Poyarkova 1987), are figured here (Fig. 17). In taxonomic composition, the C–T foraminiferal fauna from the Naiba River valley is transitional between the *Ammobaculites* Association of Haig (1979) and a so-called "flysch-type" fauna (Gradstein & Berggren 1981). According to Haig (1979), the *Ammobaculites* Association is most conspicuous in non-carbonate terrigenous deposits, especially dark grey mudstones and siltstones of shallow seas. A flysch-type fauna shows little depth restriction, except that usually it is >200 m, and it seems more closely associated with relatively rapid deposition of organic-rich, carbonate-poor, and fine-grained clastics (Gradstein & Berggren 1981).

Radiolarians

A zonal subdivision has been established on the succession of C–T radiolarian assemblages identified in Sakhalin (Fig. 5, 18). During the Albian, numerous representatives of the genus *Crolanium*, with a triangular or quadrangular distal skeletal section, are dominant. Cenomanian radiolarians differ strongly from those of the Albian. However, there are also some long-ranging taxa that continued through the Cenomanian into the Turonian and Coniacian. For example, the Spumellaria were represented in the Cenomanian and Turonian by two genera, *Orbiculiforma* and *Phaseliforma*. The Nassellaria comprises many representatives of *Archaeodictyomitra* with striated shell surface and *Amphipyndax* with complex, poreless cephalis and several postcephalic joints (Fig. 19, 20).

The early Cenomanian *Lipmanium sacramentoensis – Archaeodictyomitra squinaboli* Zone (Fig. 19) yields more than 20 species, 9 of which are long ranging from the Albian onwards and 13 of which appear first in the basal Cenomanian. In an earlier paper (Kazintsova 2000), representatives of the genera *Haliomma*, *Cromyodrimus*, *Stylodruppa*, *Lipmanium*, *Theocorys*, and *Stichomitra* were recorded. Generally, spherical skeletons with numerous long spines (e.g., *Actinomma*, *Haliomma*, *Cromyodrimus*) and nodose skeleton structures (*Praeconocaryomma*) dominate in the lower Cenomanian. In addition, elliptical skeletons with some inner concentric rings (genera *Cromyodruppa* and *Stylodruppa*) are observed. The Nasselaria is represented by species of the genus *Lipmanium* which have 'hat'-like, double-chambered skeletons with a thorax rim. Six species in this assemblage went extinct at the end of the Cenomanian.

The late Cenomanian *Haliomma sachalinica – Dictyomitra multicostata* Zone (Fig. 20) has yielded more than 20 species, 13 of which are long ranging and 8 are new appearances. At this level, representatives of *Patulibracchium* with a brachiopyle at the end of three primary rays, of

Cavaspongia with biconvex shells, and of *Acanthocircus* with simple elliptical rings, are found for the first time. At the end of the Cenomanian, 10 species died out.

The early Turonian *Crucella cachensis – Alievium superbum* Zone comprises nearly the same taxonomic assemblage. No abrupt change has been noted at this level. Generally, most species continued from the Cenomanian into the Turonian and just a few made their first appearance, for example, representatives of the genus *Crucella* (Fig. 20). Skeletons of this genus consist of four crossed rays, with a central reduction and often with a patagium.

In total, the lower–middle Turonian has yielded 15 species, 4 of which disappeared in the middle–upper Turonian interval, after which there is a gap in data (Fig. 5, 18). The next radiolarian assemblage (late Turonian to early Coniacian *Orbiculiforma quadrata – O. monticelloensis* Zone (Fig. 20)) is comparatively poor in taxa and in individuals; the few species represented mostly belong to the long-ranging genus *Orbiculiforma*.

Thus, in total, 39 radiolarian species have been identified in the C–T succession of Sakhalin, 28 of them belonging to the Spumellaria (17 genera), and 11 referred to the Nasselaria (9 genera; see Kazintsova in Poyarkova 1987; Zonova et al. 1993). There is a marked faunal turnover near the middle/upper Turonian boundary.

Globally, productivity event at the C/T boundary (OAE2) had a major effect on radiolarians (see Leckie at al. 2002, fig. 7). In contrast, the radiolarian fauna from Sakhalin appears to have survived this interval without marked taxonomic change. A diversity decrease took place later, near the middle/upper Turonian boundary. However, at this level there is an interval that does not yield any radiolarian data (Fig. 5).

Comments on paleoenvironment and paleoecology

Based on analyses of fossil associations and lithological changes, it is possible to reconstruct a broad paleo-environmental history of the C–T succession in Sakhalin, which was deposited in an open shelf basin of an active marginal sea (Kirillova 1997; Kirillova et al. 2000). Generally, this interval is well known globally as the most dynamic mid-Cretaceous time slice, associated with greenhouse climates, a sea-level highstand, and a warming peak followed by an abrupt basal Turonian cooling (Barnes et al. 1995). Many regional studies have shown that the C–T transgression was relatively long lasting and was interrupted by brief episodes of regression due mostly to local tectonics (see, amongst others, Matsumoto 1980; Naidin et al. 1980; Hallam 1992).

Paleotemperature studies have shown the climate to have ameliorated in Sakhalin at the end of the middle Cenomanian (Kirillova et al. 2000). The highest ammonite diversity is in the middle Cenomanian (*Acanthoceras sussexiense* Zone). This part of the succession, from Member 4 (Naiba Formation) to Member 2 of the Bykov Formation (Fig. 3, 4), records initially quiet sedimentation in a relatively deep water marine environment, suggested by the dominance of the inoceramid group with large, flat shells and weakly developed sculpture (e.g., *Inoceramus pressulus*, *I. gradilis*, and *I. pennatulus)* and plano-spiral ammonites with well-developed shell ornament, occasionally with coarse ribs (e.g., *Mantelliceras* and *Calycoceras*). Mostly these are morpho-types of Group C (Tanabe et al. 1978); a smaller percentage belongs to Group A (Tanabe 1979; Westermann 1996). Heteromorph ammonites of Group B are represented by relatively rare specimens of the genus *Turrilites*. Non-heteromorph ammonites have platycone, discocone, and spherocone shell shapes (*sensu* Westermann 1996). These shell forms suggest open, offshore marine settings (Tanabe 1979; Tsujita & Westermann 1998). Moreover, rare finds of torticone heteromorphs, which Westermann (1996) considered to have been planktonic vertical migrants, and thin, flat inoceramid shells also provide evidence for relatively deep yet warm water. The abundance of radiolarians points to high persistence of silica and other nutrient loadings (see Racki & Cordey 2000, literature review on pp. 23–25). The most abundant radiolarian assemblages have been collected from the basal upper Cenomanian. Relatively deeper environments are also indicated by the number of elongated or flattened radiolarian skeletons in Cenomanian assemblages (Casey 1993).

Subsequently, a brief regressive episode marked by the "coloured barren interval" of Member 3 (Bykov Formation) could be an expression of the combined effect of regional tectonism and volcanism. Whereas, most Cenomanian ammonite, inoceramid, and foraminifera species disappeared, there was almost no change in the species composition of radiolarians.

OAE2, as recorded in Hokkaido by Toshimitsu & Hirano (2000), could possibly correlate with the black mudstones in the middle portion of Member 2 of the Bykov Formation (Fig. 3). Moreover, the Hokkaido sections generally are characterised by similar patterns across the C/T boundary interval: a barren interval, a green and grey sandstone, black shales, and positive ^{13}C values (Hirano & Takagi 1995; Toshimitsu et al. 1995). In addition, the black shales in the uppermost part of Member 3 of the Bykov Formation, characterised by a low faunal diversity, might also be interpreted to represent an oxygen-poor paleoenvironment, associated with abrupt cooling. Unfortunately, the positive δ^{13}C spike documented across the C/T boundary in the River Naiba valley (Hasegawa et al. 2003) has been interpreted too widely, corresponding as it does to an interval of 200 m, and lacking detailed biostratigraphy. With these data in hand it is extremely difficult, if not impossible, to establish a detailed correlation.

However, it is interesting to note that a similar succession is present in New Zealand, suggesting that this may be a signal of wider environmental events. In New Zealand, recent data (J. Crampton pers. comm.) indicate a conspicuous excursion in δ^{13}C (terrestrial) occurring in the Mangaotane Stream section, at about the same level as the lowest occurrence of conspicuous red beds. Relatively positive ^{13}C values persist through an interval of red and green beds which is, in part, barren of inoceramids (see Crampton et al. 2001, fig. 3). Thus, there is a pattern in New Zealand which is closely comparable to that observed in Sakhalin, Korjakia Upland (authors' field obs), and Japan: coloured beds, a carbon isotope excursion, and a barren interval.

Zakharov et al. (1996, 1999) documented relatively high paleotemperature (near 15°C) only at the end of the Turonian, based on isotope analyses of aragonitic ammonites shells from southern Sakhalin and Hokkaido. The late Turonian warming is associated with a significant decrease in microfaunal diversity. The taxonomic increase in macrofauna both in benthic and planktonic groups, especially in heteromorphy ammonites, occurred approximately in the
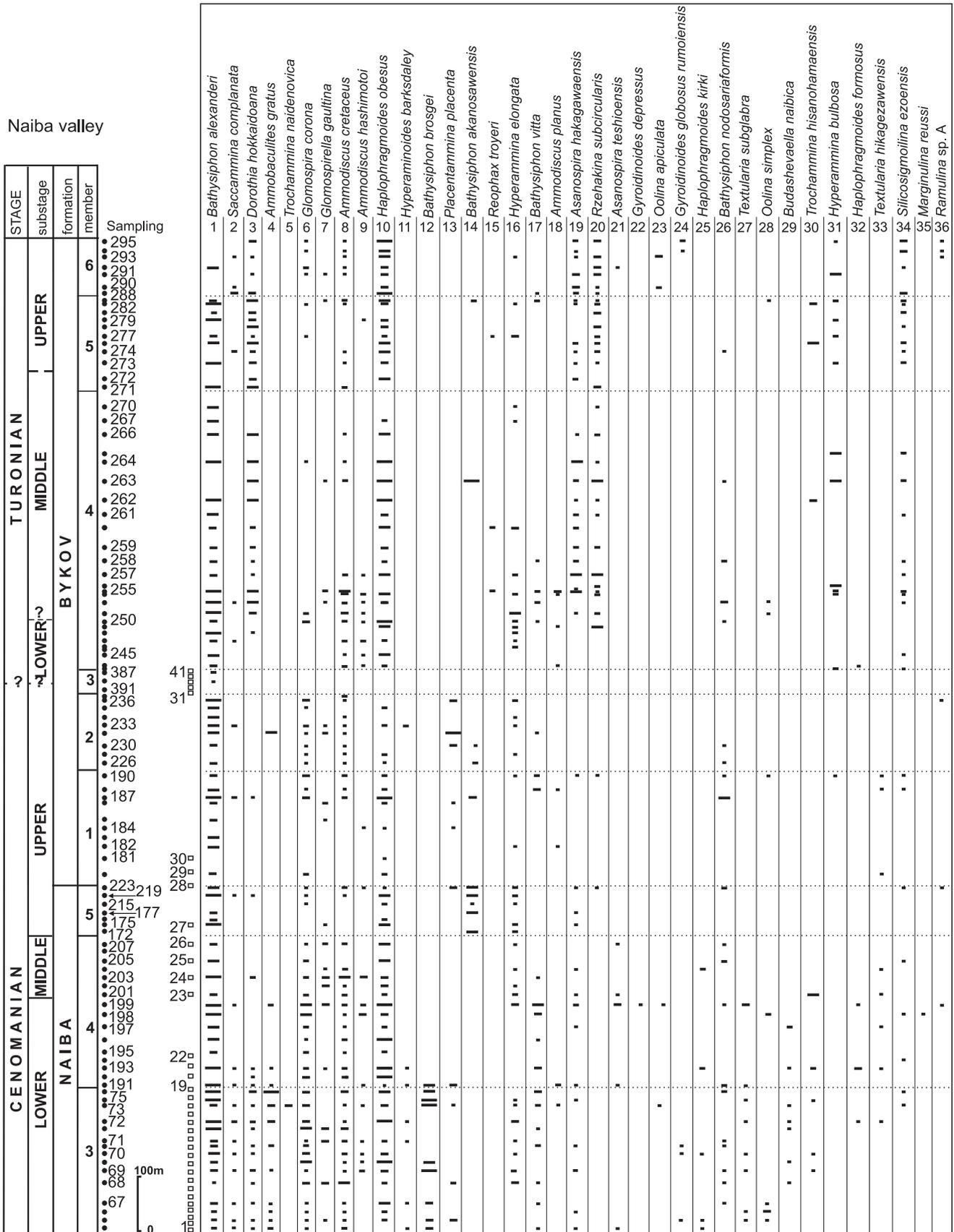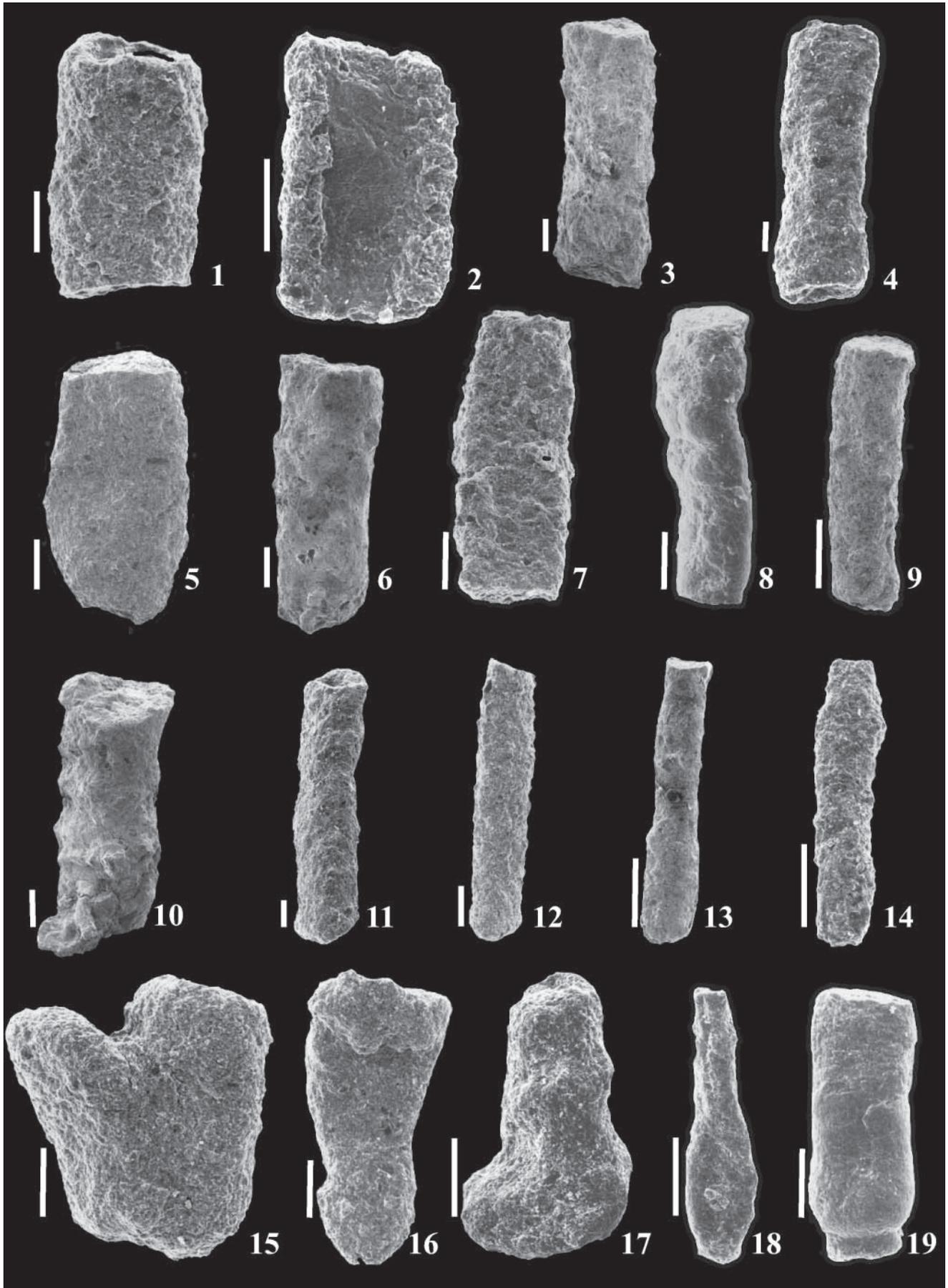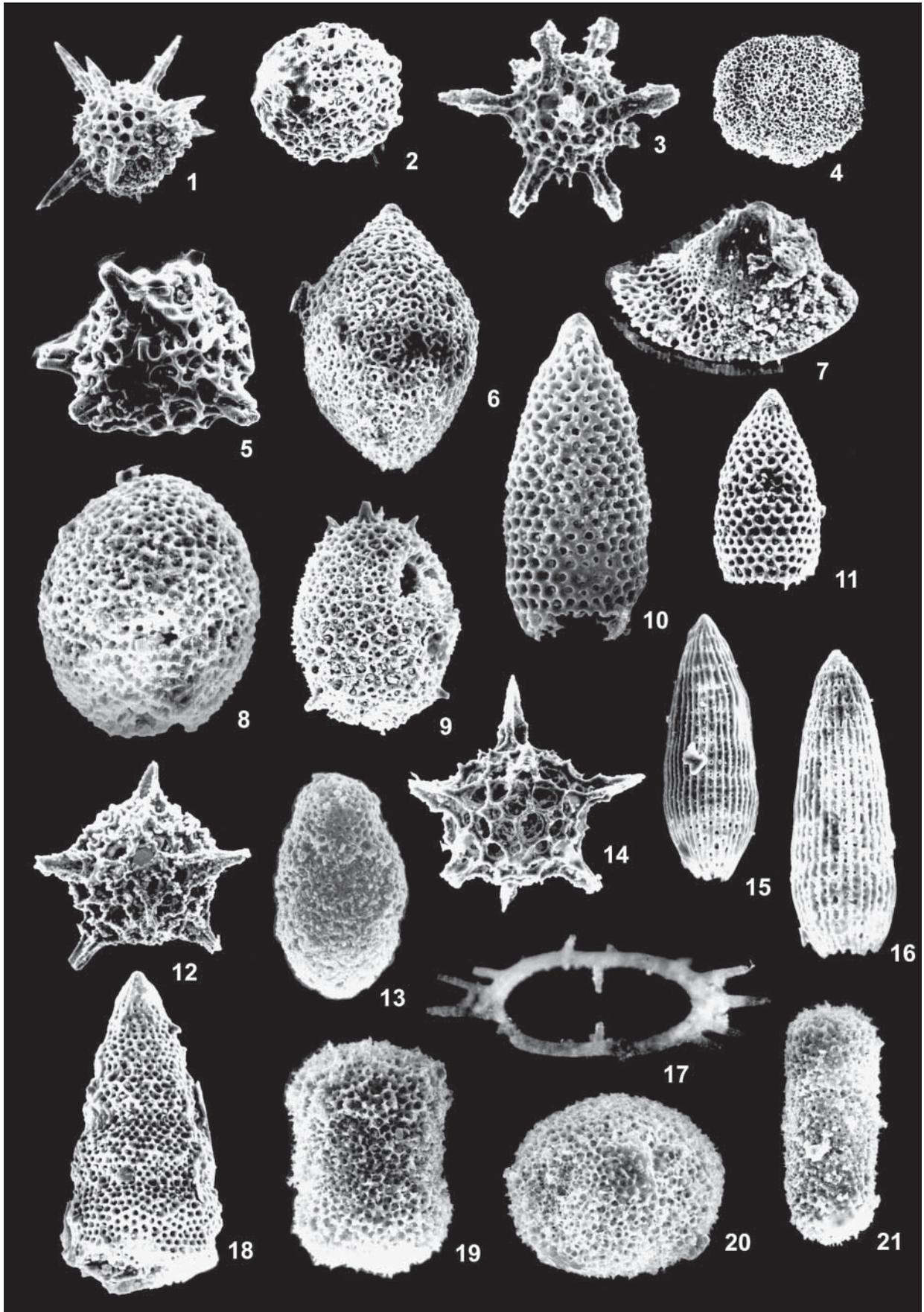
Fig. 16   Stratigraphic distribution of Cenomanian–Turonian foraminifera species (part of fig. 23 from Turenko in Poyarkova 1987, modified).

37 *Dentalina catenula*
38 *Saracenaria pseudonavicula*
39 *Hemirobulina nagaoi*
40 *Haplophragmoides* ex gr. *excavatus*
41 *Dentalina nana*
42 *Whiteinella brittonensis*
43 *Archaeoglobigerina cretacea*
44 *Whiteinella* sp.
45 *Lenticulina firma*
46 *Whiteinella portsdownensis*
47 *Hedbergella delrioensis*
48 *Hedbergella planispira*
49 *Silicosigmoilina futabensis*
50 *Nuttalides takayanagii*
51 *Planulina rumoiensis*
52 *Pseudopatellinella cretacea*
53 *Trochammina yubarensis*
54 *Asanospira orlovica*
55 *Silicosigmoilina sagabei*
56 *Astacolus polandensis*
57 *Lenticulina* cf. *heiermanni*
58 *Spirosigmoilinella gorbushensis*
59 *Lenticulina ezoensis*
60 *Lenticulina matsumotoi*
61 *Alabamina dorsoplana*
62 *Citharina geisendorferi costata*
63 *Pseudofrondicularia lanceala*
64 *Lenticulina yabei*
65 *Dentalina praecommunis*
66 *Frondicularia inversa*
67 *Enantiodentalina* sp.
68 *Marssonella oxycona*
69 *Marginotruncana* sp.
70 *Marginulina texanensis*
71 *Marginulina bullata*
72 *Citharina penna*
73 *Stilostomella* cf. *stephensoni*
74 *Pleurostomella subnodosa*
75 *Lenticulina oblonga*
76 *Lingulina pygmaea*
77 *Lenticulina obirashibensis*
78 *Globorotalites conicus*

Silicosigmoilina futabaensis - Rzehakina subcircularis Zone

Glomospira corona - Ammobaculites gratus Zone

Number of specimens
> 50
25 - 50
11 - 25
6 - 10
1 - 5

Sampling
• Turenko (1987)
▫ this study

Fig. 16 *(continued)*

Fig. 18 Stratigraphic distribution of Cenomanian–Turonian radiolarian species.

middle Turonian. The worldwide acme of Turonian ammonites and inoceramids has already been noted and described in previous works for the northern Pacific (Noda & Matsumoto 1998; Zonova & Yazykova 1998), the Crimean Peninsula (Vejmarn et al. 1998), and for Germany and Poland (Walaszczyk 2000).

According to Tanabe (1979), the increase in heteromorphs (morphotypes of Group B) during the middle Turonian, in particular in the widely distributed *Scaphites* facies, and the appearance of new representatives of Group A (*Romaniceras*, *Fagesia*, *Subprionocyclus*), provide evidence of inshore shallow-water habitats (near 50–80 m depth). Moreover, numerous *Nipponites* and *Scalarites* (Fig. 9, 10) apparently

preferred shallower basins. *Scaphites planus* and *Yezoites puerculus* are both found in close association with small aptychi, which is why these specimens are regarded as autochthonous. The high diversity within Group C (*Anagaudryceras*, *Gaudryceras*, *Zelandites*, *Tetragonites*, *Jimboiceras*, *Tragodesmoceroides*, and *Neophylloceras*) may possibly be linked to the fact that morphotypes of Group C were adapted to wider habitats ranging from inshore shallow water to offshore deep water, in contrast to other morphotypes (Tanabe 1979).

The most typical representatives of Turonian inoceramids are species with new shell morphotypes and well-developed sculpture (e.g., *Inoceramus hobetsensis* and *I. iburiensis*).

Fig. 17 Some representatives of the Turonian foraminifers from the River Naiba valley. **1, 2, 7** *Bathysiphon gerochi* Myatlyuk, ZPAL F.49/1, ZPAL F.49/2, ZPAL F.49/7. **3, 4, 5** *Bathysiphon vitta* Nauss, ZPAL F.49/3, ZPAL F.49/4, ZPAL F.49/5. **6, 10** *Bathysiphon akanosawensis* Takayanagi, ZPAL F.49/6, ZPAL F.49/10. **8, 9** *Bathysiphon alexanderi* Cushman, ZPAL F.49/8, ZPAL F.49/9. **11, 12** *Rhabdammina cylindrica* Glaessner, ZPAL F.49/11, ZPAL F.49/12. **13, 14** *Bathysiphon brosgei* Tappan, ZPAL F.49/13, ZPAL F.49/14. **15**, *Dendrophrya* sp., ZPAL F.49/15. **16**, *Hyperammina* sp., ZPAL F.49/16. **17**, *Hyperammina elongata* Brady, ZPAL F.49/17. **18, 19** *Bathysiphon discreta* (Brady) ZPAL F.49/18, ZPAL F.49/19. All samples are from Member 4 of the Bykov Formation, River Naiba valley, middle Turonian. Scale bar = 200 μm.

These morphotypes dominate throughout the Turonian. The relatively shallow and warm, agitated and well-oxygenated habitats, with normal salinity, may have allowed a proliferation of inoceramids and non-inoceramid bivalves; in addition, energy/dynamics may have been higher in comparison to the Cenomanian, based on the common occurrence of bivalves with heavily ornamented, thick shells. The late Turonian radiolarian assemblage consists of mostly warm-water, spherical and subspherical, biconvex forms, which are also shelf tolerant (Casey 1993). Moreover, the deposits at the base of Member 5 (Bykov Formation; Fig. 11) have yielded numerous, adult *Inoceramus* ex gr. *lamarcki*, which form coquina beds a few centimetres in thickness. Similar events are known from the northwestern coast of Kamchatka and from the Western Interior of the United States, with *Inoceramus ginterensis* Pergament (Sageman et al. 1997).

Foraminiferal data, in particular those in the present study and those supplied by Turenko (in Poyarkova 1987), indicate a gradual deepening of the basin during the late Cenomanian and Turonian. The water depth of the basin in which the upper part of the Naiba Formation (Members 3–5) accumulated, that is, during the early and middle Cenomanian, is estimated to have been a shallower shelf, as based on the absence of planktonic foraminifera in this interval and the common to abundant occurrence of organic-cemented, siliceous agglutinated types. The successive appearance of planktonic foraminifera in the Bykov Formation, that is, globular forms (*Hedbergella* and *Whiteinella*) in the basal part (base of Member 1) and keeled forms (*Archaeoglobigerina* and *Marginotruncana*) in the upper part (Members 5 and 6) (Turenko in Poyarkova 1987, fig. 15), indicate deepening of the basin to outer shelf depth during the late Cenomanian and Turonian, following the bathymetric models discussed by Haig (1979), Hart & Bailey (1979), and Gradstein & Berggren (1981).

DISCUSSION

At the Second International Symposium on Cretaceous Stage Boundaries (Brussels, 1995) it was recommended that the main criteria for the recognition of the C/T boundary and for the lower/middle Turonian boundary are the first appearances of the ammonite *Watinoceras devonense* and *Collignoniceras woollgari*, respectively (see Bengtson 1996). Neither of these species has been recorded from Far East Russia; thus, only a detailed study of biotic and abiotic events can provide the nessesary data for regional and global correlation.

The C/T mass extinction event is well known in different regions of the world, including Far East Russia. The present study documents the abrupt macrofaunal change in the Sakhalin paleobasin well, namely for ammonites and inoceramids. No Cenomanian taxa survived this crisis. The extinction of the family Acanthocerataceae at the end of the Cenomanian and the wide distribution of heteromorph ammonites, particularly the development of the *Scaphites* facies in the Turonian, are marked during this interval both in the Pacific and European Realms (Tanabe 1979; Kaplan et al. 1987; Hirano et al. 2000). The disappearance of *Pergamentia*-group inoceramids in Far East Russia can be correlated with the extinction of the *I. pictus* group in European areas and the Western Interior of the United States. Similarly, the *Mytiloides* event that characterises the base of the Turonian, as well as the wide distribution of the "*lamarcki*" group throughout the Turonian, have been noted in many regions (Walaszczyk 1988; Harries et al. 1996; Kennedy et al. 2000).

During the C/T boundary event, foraminifera did not suffer a catastrophic mass extinction and just a single planktonic genus, *Rotalipora*, became extinct. Benthic foraminiferal assemblages, however, do exhibit various degrees of temporary faunal restructuring even in the absence of a major extinction (e.g., Jarvis et al. 1988; Peryt & Wyrwicka 1991, 1993; Kuhnt 1992; Kaiho et al. 1993; Kaiho & Hasegawa 1994; Coccioni et al. 1995; Lamolda & Peryt 1995; Peryt & Lamolda 1996; Paul et al. 1999). The major foraminiferal turnover occurred in the latest Cenomanian. In Member 2 of the Bykov Formation, an accelerated stepwise disappearance within benthic foraminiferal faunas is visible. Two species became extinct; others disappeared only temporarily. This sequence of events was terminated by the near-complete removal of benthic foraminifera within the "barren interval" in Member 3. Only rare specimens of *Bathysiphon alexanderi* have been reported from there (Turenko in Poyarkova 1987, fig. 15). However, the foraminiferal faunas recovered very rapidly. In the lower part of the overlying Member 4, the first Lazarus taxa return, followed by new species appearances (Turenko in Poyarkova 1987). Foraminiferal assemblages again became moderately abundant and diverse in the early Turonian. A rapid recovery in the early Turonian and a return of Lazarus taxa have recently been recorded for foraminifera and calcareous nannoplankton from Tibet (Xiaoqiao et al. 2003).

In the radiolarians, a remarkable faunal turnover is noted near the middle/upper Turonian boundary, in contrast to other regions in the world (Leckie et al. 2002). No extinction has been established at the C/T boundary and the early Turonian radiolarian assemblage consists of 50% of long-lived species, which continued from the early Cenomanian into the Coniacian.

Recently, Smith et al. (2001) have suggested that the C/T "extinction event" was not an extinction at all, but an artefact of sea-level changes and biased preservation of particular facies. Following Smith et al., planktonic forms (foraminifera and radiolarians) were not affected by the C/T boundary, while benthic taxa were. Generally, it might appear

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◀ **Fig. 19**   The radiolarian collection N421, lower–middle Cenomanian, *Lipmanium sacramentoensis – Archaeodictyomitra squinaboli* Zone, River Naiba valley: **1**, *Actinomma* (?) *davisensis* Pessagno, ×120; **2**, *Praeconocaryomma lipmanae* Pessagno, ×150; **3**, *Cromyodrimus mirabilis* Squinabol, ×120; **4**, *Porodiscus* sp., ×95; **5**, Gen. et sp. indet., ×250; **6**, *Theocorys* ex gr. *antiqua* Squinabol, ×130; **7**, *Lipmanium sacramentoensis* Pessagno, ×195; **8**, Gen. et sp. indet., ×325; **9**, *Stylodruppa tumefacta* Kasinzova, ×100; **10**, *Amphipyndax stocki* (Campbell & Clark), ×240; **11**, *Amphipyndax ellipticus* Nakaseko & Nishimura, ×200; **15, 16** *Archaeodictyomitra squinaboli* Pessagno: 15 ×110, 16 ×130; **18**, *Stichomitra communis* Squinabol, ×205, upper Cenomanian, *Haliomma sachalinica – Dictyomitra multicostata* Zone, River Naiba valley; **12, 14** *Haliomma sachalinica* Kasinzova, ×150; **13**, *Phaseliforma meganosensis* Pessagno, ×200; **17**, *Acanthocircus* ex gr. *brustolensis* (Squinabol), ×100; **19**, *Spongurus* ? sp., ×250; **20**, *Orbiculiforma* ? sp., ×200; **21**, *Spongurus porrectum* Kasinzova, ×200.
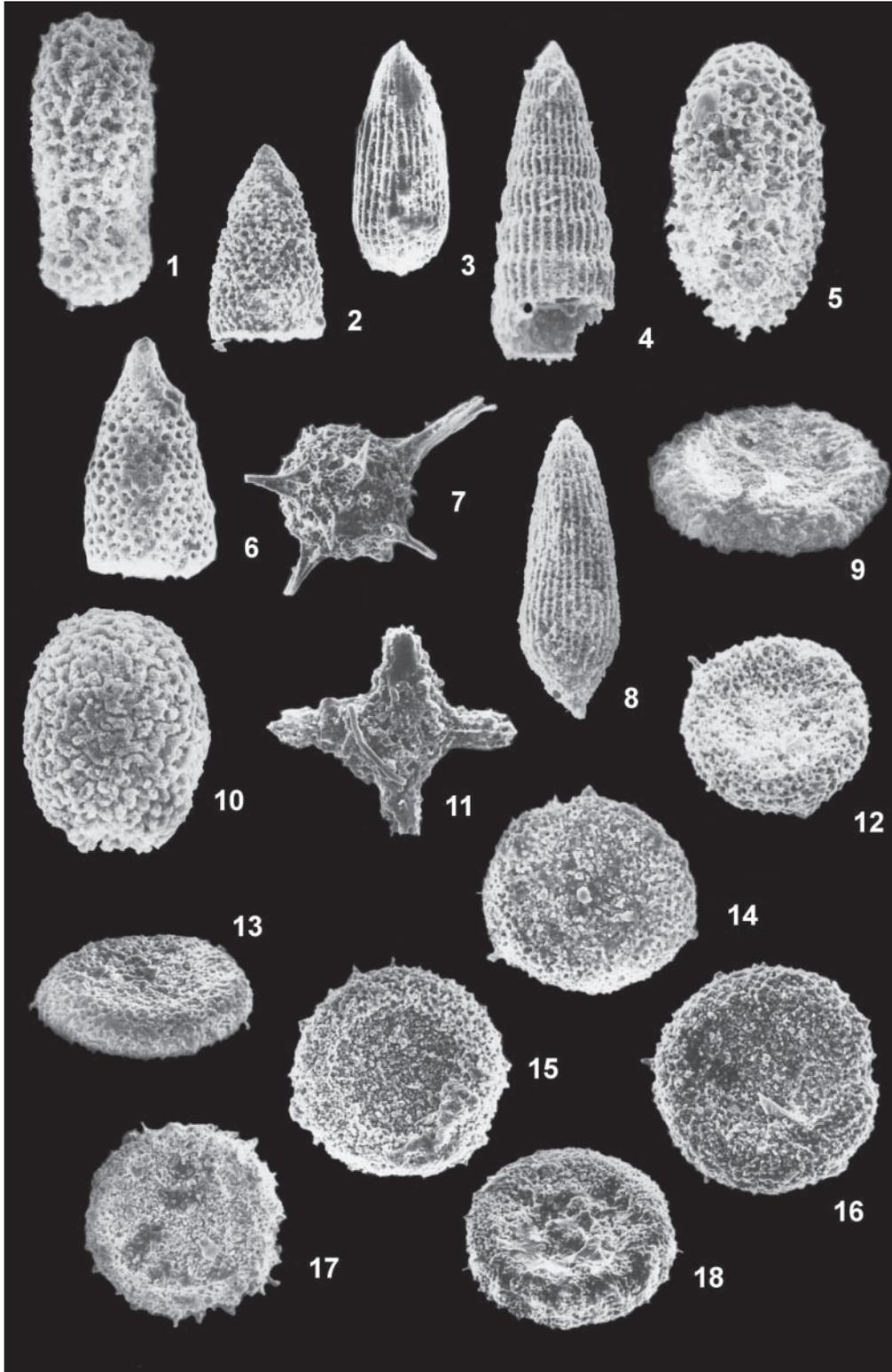
Fig. 20 The radiolarian collection N421, River Naiba valley. Upper Cenomanian, *Haliomma sachalinica – Dictyomitra multicostata* Zone: **1**, *Spongurus porrectum* Kasinzova, ×200; **2**, *Amphipyndax ellipticus* Nakaseko & Nishimura, ×150; **4**, *Dictiomitra multicostata* Zittel, ×95; **5**, *Phaseliforma* ? sp., ×120; **8**, *Archaeodictyomitra squinaboli* Pessagno, ×90; **10**, *Phaseliforma laxa* Pessagno, ×200. Lower Turonian, *Crucella cachensis – Alievium superbum* Zone: **3**, *Archaeodictyomitra squinaboli* Pessagno, ×125; **6**, *Amphipyndax stocki* (Campbell et Clark), ×200; **7**, *Actinomma* sp., ×125; **9**, *Orbiculiforma* ex gr. *cachensis* Pessagno, ×125; **11**, *Crucella* cf. *cachensis* Pessagno, ×100; **13, 14** *Orbiculiforma monticelloensis* Pessagno, ×145. Upper Turonian to lower Coniacian, *Orbiculiforma quadrata – O. monticelloensis* Zone: **12**, *Orbiculiforma quadrata* Pessagno, ×120; **15, 17** *Orbiculiforma monticelloensis* Pessagno, ×90; **16**, *Orbiculiforma* ex gr. *persenex* Pessagno, ×80; **18**, *Orbiculiforma* sp., ×80.

as if the results of the present work would support such a model. This needs to be discussed. On the one hand, data on radiolarians differ from other regions in the world, as outlined above, and further research is required. On the other, we cannot be absolutely certain that planktonic foraminifera were not affected in Sakhalin because of the absence of planktonic species in samples N1–41 (see Fig. 16) and on account of only few, poorly preserved, indeterminate specimens in Turenko's material (Poyarkova 1987). This pattern may be consistent either with insufficient collecting and/or taphonomic processes. Numerous publications demonstrate a major extinction of foraminifera (e.g., Jarvis et al. 1988; Peryt & Wyrwicka 1991, 1993; Kaiho et al. 1993; Vejmarn et al. 1998; Paul et al. 1999). Moreover, Xiaoqiao et al. (2003) have just noted the C/T boundary in southern Tibet to be a major extinction of foraminifera (both benthic and planktonic forms) and calcareous nannoplankton, well correlatable with patterns documented for England (Jarvis et al. 1988), Japan (Kaiho & Hasegawa 1994), Poland (Peryt & Wyrwicka 1991), and the Western Interior of the United States (Eicher & Worstell 1970). New material from Sakhalin may enable us to present more detailed data on planktonic foraminifera and radiolarians in the future.

CONCLUSIONS

1. The C–T interval of the Cretaceous succession in Sakhalin (Far East Russia) has yielded a rich record of moderately well preserved ammonites, inoceramids, radiolarians, and benthic foraminifera, consisting of mostly endemic species and few cosmopolitan forms.

2. The C/T boundary in Far East Russia is placed within the 30–50 m thick "coloured barren interval", which can be traced from Japan through Sakhalin to Korjakia Upland, and forms an excellent lithologic marker horizon.

3. The base of the Turonian in Far East Russia is recognised on: the FO of *Mytiloides* aff. *labiatus* and the wide distribution of inoceramids of the *lamarcki* group; the FO of the ammonite *Jimboiceras planulatiforme* that is widely distributed in the north Pacific Province; and the occurrence of *Fagesia* and *Romaniceras* (*Yubariceras*) *ornatissimum*.

4. A significant macrofaunal turnover and radiation has been identified across the C/T boundary in Far East Russia. In addition, there was a significant faunal turnover of ammonites in the middle Turonian and of inoceramids in the upper Turonian. Subsequent to the major faunal turnover at the C/T boundary, the evolution of ammonites and inoceramids proceeded at different rates.

5. The levels of ammonite and inoceramid extinction, radiation, and high diversity can be correlated with the same time levels in European and Mediterranean Realms.

6. Microfaunal analyses show that foraminiferal assemblages exhibit no major extinction at the C/T boundary, but temporary faunal restructuring did take place. The radiolarian fauna appears to have survived this interval without marked taxonomic change, with the diversity decrease occurring later, near the middle/upper Turonian boundary.

7. A high-resolution, integrated biostratigraphic zonation based on ammonites, inoceramids, radiolarians, and benthic foraminifera is proposed and correlated with adjacent areas. The zonal scheme comprises 10 ammonite, 7 inoceramid, 4 radiolarian, and 2 foraminiferal zones.

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